



Addressing the dissipation of mineral resources in life cycle assessment : Improving concepts and development of impact assessment methods for 61 metals

Alexandre Charpentier Poncelet

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POUR OBTENIR LE GRADE DE
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Par Alexandre CHARPENTIER PONCELET

**ADDRESSING THE DISSIPATION OF MINERAL
RESOURCES IN LIFE CYCLE ASSESSMENT**
**Improving Concepts and Development of Impact Assessment Methods for
Sixty-one Metals**

Sous la direction de : Guido SONNEMANN

Soutenue le 30/11/2021

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Prise en compte de la dissipation de ressources minérales en analyse du cycle de vie: amélioration des concepts et développement de méthodes d'évaluation d'impact pour 61 métaux

Résumé : Les flux dissipatifs de ressources minérales sont au cœur de l'évaluation de l'impact environnemental, car ils sont nocifs pour l'environnement et représentent un gaspillage de ressources non renouvelables. L'analyse du cycle de vie (ACV) est un outil d'évaluation environnementale reconnu encadré par les normes ISO 14040/44, visant généralement à prévenir les impacts sur trois aires de protection: la santé des écosystèmes, la santé humaine, et les ressources naturelles. Traditionnellement, l'impact de l'extraction sur l'épuisement des ressources minérales a été évalué pour mesurer l'impact sur l'aire de protection ressources naturelles. Cependant, les tendances récentes des discussions au sein de la communauté ACV suggèrent que la dissipation des minéraux peut être plus pertinente à évaluer, car elle représente la perte réelle de matériaux qui ne sont plus accessibles pour une utilisation future, alors que l'épuisement des stocks géologiques peut en fait être considéré souhaitable tant et aussi longtemps que les ressources minérales restent accessibles pour une réutilisation future.

Cette thèse a pour objectif d'améliorer la prise en compte des flux dissipatifs de ressources minérales dans le cadre de l'ACV, en particulier sur l'aire de protection des ressources naturelles. D'une manière générale, deux thèmes sous-jacents sont inclus dans l'objectif: améliorer la compréhension des impacts de l'utilisation des ressources minérales sur l'aire de protection ressources naturelles, et développer une méthode d'évaluation des impacts environnementaux permettant de quantifier ces impacts en relation avec la dissipation des ressources minérales.

Nous étudions d'abord les impacts reliant les interventions humaines à l'aire de protection ressources naturelles. Cette étude permet d'établir les liens entre les flux de ressources minérales et l'aire de protection, afin de fournir un cadre cohérent pour évaluer les impacts de l'utilisation des ressources minérales sur celle-ci en utilisant plusieurs méthodes d'évaluation des impacts à la fois. Ensuite, nous explorons les concepts et la terminologie entourant la dissipation et proposons un cadre conceptuel pour aborder la dissipation des ressources minérales en utilisant des données d'analyse de flux de matière dynamiques. Deux options sont identifiées : retravailler les inventaires de cycle de vie actuels pour intégrer les flux dissipatifs et développer une méthode d'évaluation de l'impact du cycle de vie appropriée, ou proposer une méthode d'évaluation des impacts intégrant la dissipation dans le calcul de ses facteurs de caractérisation et qui peut être appliquée directement aux flux d'extraction dans les données d'inventaires actuelles. La deuxième option est retenue pour la suite de la thèse.

Des données sont collectées pour 61 éléments métalliques et des résultats d'analyse de flux de matière dynamique sont obtenus pour ces derniers. Nous proposons alors deux méthodes pour mesurer l'impact de la dissipation sur les ressources minérales : le taux de dissipation moyen (ADR, pour « average dissipation rate ») et le temps de service potentiel perdu (LPST, pour « lost potential service time »). A partir des résultats d'analyse de flux de matière dynamique, des facteurs de caractérisation midpoint sont calculés pour 61 métaux. En outre, les facteurs de caractérisation endpoint sont proposés à l'aide d'un indice basé sur les prix. Enfin, les facteurs de caractérisation sont appliqués à un large éventail d'ensembles de données d'inventaires de cycle de vie afin d'observer les tendances à attendre dans les études ACV couvrant la dissipation des ressources minérales en utilisant les méthodes développées. Ces résultats sont comparés à ceux d'autres méthodes fréquemment utilisées pour évaluer les impacts de l'utilisation de ressources minérales.

Mot clés: analyse du cycle de vie, dissipation, ressources minérales, métaux, impacts environnementaux, aire de protection ressources naturelles

Addressing the dissipation of mineral resources in life cycle assessment: Improving concepts and development of impact assessment methods for 61 metals

Abstract: Dissipative flows of mineral resources are central to environmental impact assessment, since they are harmful to the environment and embody a wasteful use of non-renewable resources. Life Cycle Assessment (LCA) is a recognized environmental assessment tool framed by the ISO 14040/44 norms, typically aiming to prevent damage on three areas of protection (AoP): ecosystem health, human health, and natural resources.

Traditionally, the depletion of mineral resources has been assessed to quantify impacts on the AoP natural resources. However, recent trends in discussion within the LCA community suggest that dissipation of minerals may be more relevant to assess, since they represent the real loss of materials that are no longer accessible for future use, whereas the depletion of geological stocks may actually be considered to be desirable for as long as mineral resources remain accessible for further human use.

This thesis has the objective to improve the consideration of dissipative flows of mineral resources in the LCA framework, focusing on the AoP natural resources. Broadly speaking, two topics are encompassed within the objective: improving the understanding of the impacts of mineral resource use on the AoP natural resources, and developing a life cycle impact assessment (LCIA) method allowing to quantify these impacts in relation to the dissipation of mineral resources.

We first investigate the impact pathways relating human interventions to the AoP natural resources. The relation between resource flows and the AoP natural resources is studied in order to provide a coherent framework to assess the impacts of mineral resource use on the AoP using multiple LCIA methods at once. Then, we explore concepts and terminology surrounding dissipation and propose a conceptual framework to address the dissipation of mineral resources based on dynamic material flow analysis (MFA) data. Two options are identified: reworking current life cycle inventories to integrate dissipative flows and develop a life cycle impact assessment (LCIA) method accordingly, or propose a LCIA method that integrates dissipation in the calculation of its characterization factors that can be applied to extraction flows in the current inventories. The second option is further developed in this thesis.

In order to develop LCIA methods, data is collected for 61 metallic elements and dynamic material flow analysis results are computed for them. We then propose two methods to measure the impact of dissipation on mineral resources: the average dissipation rate (ADR) and the potential service time lost (LPST). Based on the dynamic material flow analysis results, midpoint characterization factors are calculated for 61 metals. In addition, endpoint characterization factors are computed using a price-based index. Finally, the characterization factors are applied to a wide range of life cycle inventory datasets in order to observe the trends to be expected in LCA studies covering the dissipation of mineral resources using the developed methods. These results are compared to those of other frequently used LCIA methods to address the impacts of mineral resource use.

Key words: life cycle assessment, dissipation, mineral resources, metals, environmental impacts, natural resources area of protection

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Acronyms and abbreviations

| | |
|---------------------|--|
| AADP | Anthropogenic extended ADP |
| ADP | Abiotic depletion potential (LCIA method) |
| ADR | Average dissipation rate (LCIA method) |
| AoP | Area of protection |
| ARP | Abiotic Resource Project |
| BRGM | French geological survey |
| CF | Characterization factor |
| CML | Leiden University's Institute of Environmental Sciences |
| DF | Dissipative flow |
| EC | European Commission |
| EDP | Environmental dissipation potential |
| EOL-RR | End-of-life recycling rate |
| F&M | Fabrication and manufacturing |
| ICMM | International Council on Mining and Metals |
| ILCD | International Reference Life Cycle Data System |
| IRP | International Resource Panel |
| ISO | International Organization for Standardization |
| JRC | Joint Research Centre |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LPST | Lost potential service time (LCIA method) |
| LPV | Lost potential value |
| MFA | Material flow analysis |
| MR taskforce | Mineral resources taskforce of the Life Cycle Initiative |
| OST | Optimal service time |
| PEF | Product Environmental Footprint |
| PGM | Platinum group metal |
| PP | Primary production |
| REC | Recycling |
| SCP | Surplus cost potential (LCIA method) |
| SDG | Sustainable Development Goal |
| SOP | Surplus ore potential (LCIA method) |
| SP | Secondary production |
| ST | Service time |
| TDR | Total dissipation rate |
| TH | Time horizon |
| TLPST | Total lost potential service time |
| TLPV | Total lost potential value |
| TPVLR | Total potential value loss rate |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| US | United States |
| USGS | United States Geological Survey |
| WM | Waste management |

Preface

This thesis was led in the CyVi Group in the Institute of Molecular Sciences (ISM), in University of Bordeaux. It was co-financed by the French Agency for the ecological transition (ADEME) and the French Geological Survey (BRGM). *Cette thèse a été menée dans le Groupe CyVi de l'Institut des Sciences Moléculaires, à l'Université de Bordeaux. Elle a été financée par l'Agence de la transition écologique (ADEME) et le Bureau de Recherche Géologique et Minière (BRGM).*



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Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G., 2021. Midpoint and endpoint characterization factors for mineral resource dissipation: methods and application to 6,000 data sets. Submitted to the *International Journal of Life Cycle Assessment*

Moreover, works from this thesis were presented in oral presentations in national and international conferences:

Alexandre Charpentier Poncelet, Philippe Loubet, Bertrand Laratte, Jacques Villeneuve, Stéphanie Muller, Guido Sonnemann (2019). Development of a conceptual framework and its associated indicator to take the dissipation of non-energetic abiotic resources into account within Life Cycle Assessment (LCA). In *16^{ème} colloque national S.mart.* Montricher-Albanne, France.

Alexandre Charpentier Poncelet, Philippe Loubet, Bertrand Laratte, Jacques Villeneuve, Stéphanie Muller, Guido Sonnemann (2019). Development of a conceptual framework and its associated indicator to take the dissipation of non-energetic abiotic resources into account within Life Cycle Assessment (LCA). In *SETAC Europe 29th Annual Meeting*. Helsinki, Finland.

Alexandre Charpentier Poncelet, Philippe Loubet, Bertrand Laratte, Jacques Villeneuve, Stéphanie Muller, Guido Sonnemann (2019). Development of a conceptual framework to take the dissipation of non-energetic abiotic resources into account within Life Cycle Assessment (LCA). In *EcoDesign 2019 - 11th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*. Yokohama, Japan.

Alexandre Charpentier Poncelet, Philippe Loubet, Bertrand Laratte, Jacques Villeneuve, Stéphanie Muller, Guido Sonnemann (2020). Towards interim characterization factors to account for the dissipation of non-energetic abiotic resource in life cycle assessment. In *SETAC Europe 30th Annual Meeting*. Dublin, Ireland (held online).

Chapter 1: Introduction

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1.1 Life cycle assessment

The life cycle assessment (LCA) methodology, as framed by the International Organization for Standardization (ISO) 14040/44: 2006 standards (ISO, 2006a, 2006b), is a relevant environmental impact assessment method to improve product designs and communicate on their greater environmental performance, as well as support public policy making (Guinée et al., 2011). LCA studies rely on a life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases, allowing to evaluate the impacts of defined systems on the environment (European Commission et al., 2010). Figure 1-1 shows the framework for LCA studies as defined in the ISO 14040 standard.

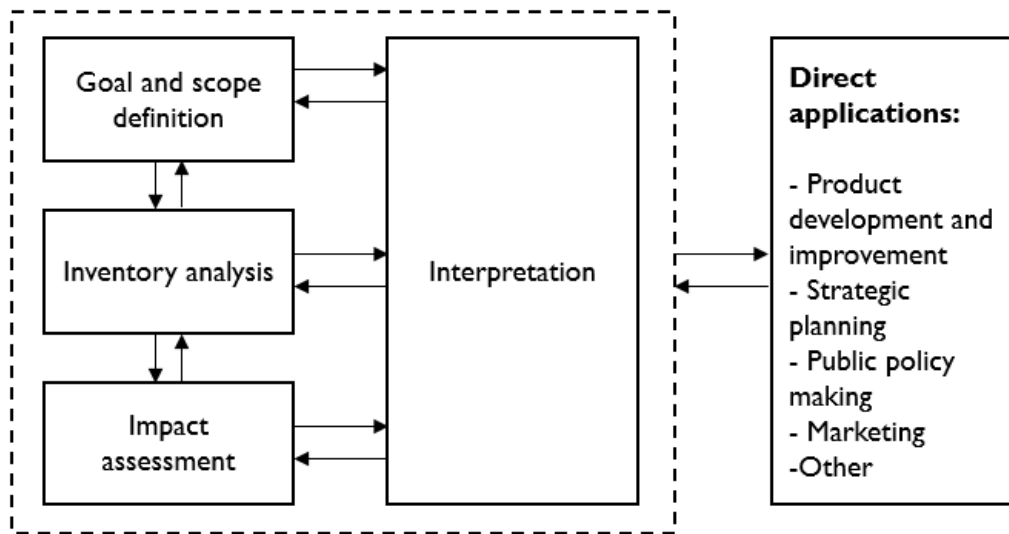


Figure 1-1. Framework of life cycle assessment according to the ISO 14040 standard

The goal and scope phase includes the definition of the studied system and of its functional unit. According to ISO (2006a), the functional unit defines the quantification of the identified functions (performance characteristics) of the product and provides a reference to which inputs and outputs are related. The LCI references each input and output for given processes and allow compiling every flows that cross the boundary between the environment and the technosphere, in relation to the defined functional unit. These flows, called elementary flows, are divided in two broad categories: resources extracted from the environment (inputs to the product system) and emissions to the environment (outputs from the product system). Relying on LCI, the LCA methodology allows summing up extraction flows of resources from the environment, and emission flows to the environment, in relation to a defined functional unit. These flows, called elementary flows, are characterized using LCIA methods allowing to assess the environmental impacts related to the functional unit. The midpoint impacts are quantified for a range of impact categories, or mechanisms, such as global warming, human toxicity, or water consumption. Each of these impact pathways may further be linked with an area of protection (AoP), in order to assess endpoint impacts, i.e., damage on the AoP. The LCIA framework typically

includes three AoPs: natural environment, human health, and natural resources (European Commission et al., 2010; Frischknecht and Jolliet, 2016). Examples of the articulation between LCI, midpoint impacts and endpoint damage are shown in Figure 1-2. In this thesis, we focus on the impacts of mineral resource use on the AoP natural resources.

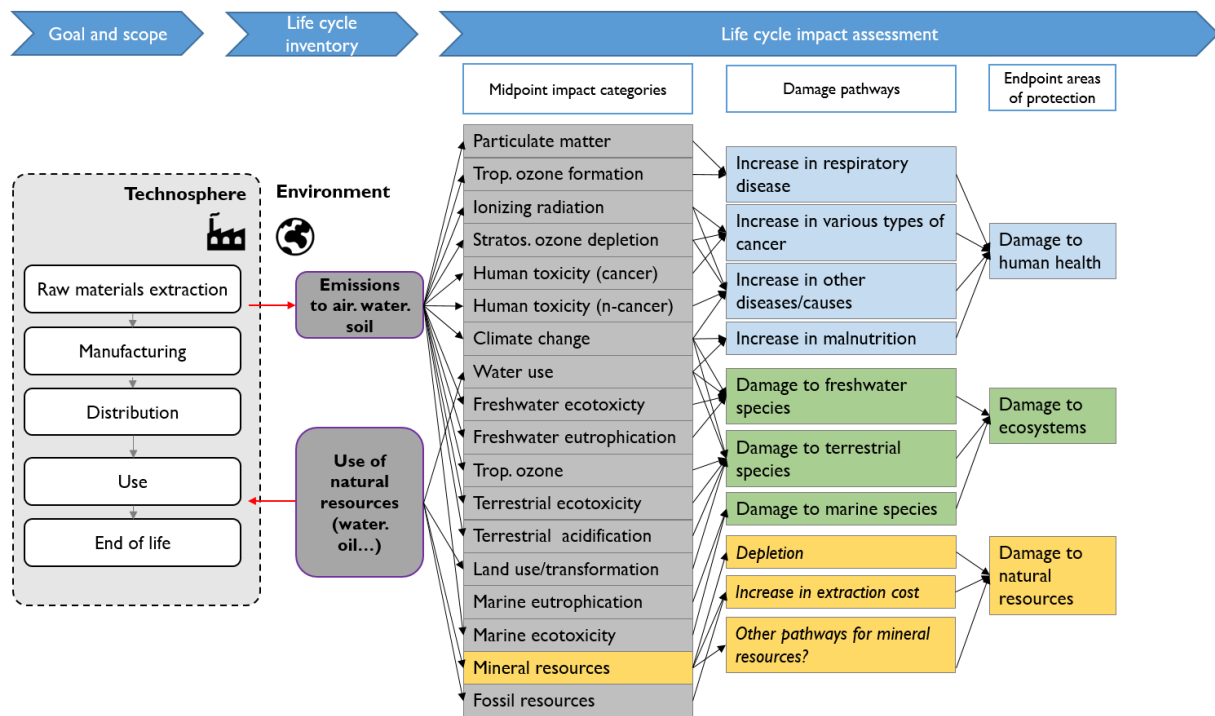


Figure 1-2. Relation between the goal and scope, life cycle inventory, midpoint and endpoint impact assessment in LCA (adapted from Huijbregts et al., 2017). The impact pathways linked to mineral resource use, indicated in yellow boxes, are investigated in this thesis.

1.2 Mineral resources in life cycle assessment

Metals and minerals (henceforth, mineral resources) support the most indispensable functions in modern societies (Graedel et al., 2013), e.g., agriculture, high technologies infrastructures, industries, medicine and transports. Over the last decades, the number of substances exploited by mankind has burgeoned, so that almost all elements of the periodic table are now used, including more than 60 metals (Greenfield and Graedel, 2013). Thus, today, we face a daunting challenge: an increasing amount of minerals is required to support modern economies while the pollution generated by their exploitation and use raises concerns about the earth's capacity to withstand it (Kesler and Simon, 2015; UNEP, 2016). A better management of resources would allow optimizing the socioeconomic value they generate for society, while keeping the associated environmental impacts in check. In recent years, important measures have been set in motion to improve the circularity and efficiency of resource use (European Commission, 2020, 2018a; United Nations, 2018).

In LCA, impacts associated to mineral resources on the AoP natural resources are attributed to extractive flows. Mineral resources originate in the natural environment likewise other resources and therefore should be an integrative part of the AoP natural resources in LCA (Sonderegger et al., 2017). Nonetheless, the consideration of natural resources as an AoP in LCA has been subject of hefty discussions in the past years (Dewulf et al., 2015; Sonderegger et al., 2017; Sonnemann et al., 2015), with dedicated attention on the consideration of the impacts related to mineral resource use (Berger et al., 2020; Drielsma et al., 2016b, 2016a; Schulze et al., 2020; Sonderegger et al., 2020). About 30 impact assessment methods have been developed that address the impacts of mineral resource use on the AoP natural resources in LCA. Most of these have been investigating the effects of extracting mineral resources on the depletion of geological reserves or on the additional efforts required to extract more resources in the future (Sonderegger et al., 2020).

Recently, the accessibility of mineral resources for humans has been identified as the key problem to be addressed in the AoP, covering both primary and secondary resources (Schulze et al., 2020; van Oers et al., 2020). Building on this, UNEP's Life Cycle Initiative task force on mineral resources (MR taskforce) has proposed a consensual definition of the safeguard subject for minerals in the AoP: "the potential to make use of the value that mineral resources can hold for humans in the technosphere" and have identified the damage as "the reduction or loss of this potential caused by human activity" (Berger et al., 2020; Sonderegger et al., 2020). Moreover, the MR taskforce grouped methods accordingly with one of seven questions they may answer to, e.g. *"how can I quantify the relative changing opportunity of future generations to use mineral resources due to current mineral resource use?"*, or *"How can I quantify the relative contribution of a product system to the depletion of resources?"* (Sonderegger et al., 2020).

However, the links between the questions and the safeguard subject identified by the MR taskforce were not clearly established. Moreover, most of the existing LCIA methods addressing mineral resource use quantify midpoint impacts, highlighting that identifying and quantifying endpoint damage on the AoP natural resources is not straightforward. For example, the extraction of minerals potentially makes resources *more* accessible to future generations for as long as resources are not made *less* accessible after their extraction through dissipation. Therefore, it seems crucial that LCIA methods link resource flows (extraction and dissipative flows) to their actual effect on the safeguard subject by answering the questions: how does depletion reduce the potential to make use of the value of mineral resources? How does dissipation reduce the potential to make use of the value of mineral resources? Finally, while a single impact pathway is most typically considered when assessing the impacts of resource use on the AoP, it seems to be necessary to consider multiple aspects related to mineral resource use to assess the impacts of their use on the AoP holistically. Finally, different human groups

may have different views of the world, and thus different opinions on how mineral resources should be used with respect to current and future generations. Thus, assessing the impacts on the AoP may need to take so-called cultural perspectives into account (see, e.g., Hofstetter, 1998 and Mamadouh, 1999).

1.3 From depletion to the dissipation of mineral resources¹

From the socio-economic perspective of the AoP Natural Resources (see discussion in Dewulf et al., 2015), resources are generally valued for the functions they provide humans with, i.e. their instrumental value (Frischknecht and Joliet, 2016; Sonderegger et al., 2017; Yellishetty et al., 2009). Resources may also provide other values leading to human well-being, such as economic and cultural values (Ardente et al., 2019). Currently, the extracted resources are considered to be the LCI flows responsible for the impact, while the global stocks (anthropogenic and geological stocks) remain unchanged unless resources have been made inaccessible through dissipation. Reducing geological stocks can mean increasing the stocks in use, which is desirable from the perspective of the functionality resources provide humans with. The safeguard subject defined by the MR taskforce reveals that the value of resources in the technosphere must be primarily protected, rather than the geological stocks. Nonetheless, the latter is evidently connected to the former for as long as primary extraction is required to satisfy human demand.

The extraction of mineral resources from the earth's crust implies a reduction of the associated geological stock. The Abiotic Depletion Potential (ADP) method using ultimate reserves is based upon such a rationale (van Oers et al., 2002; van Oers and Guinée, 2016). ADP is currently recommended by the Life Cycle Initiative to assess the contribution of a product system to the depletion of mineral resources (Berger et al., 2020). It is also currently recommended to assess the impacts of mineral resource use in the Product Environmental Footprint (PEF), although the European Commission intends to move from a depletion to a dissipation model in the future (European Commission, 2013; Zampori and Pant, 2019).

However, resources may be retained in the economy and provide humans with their functions, given a proper management. Acknowledging this, the anthropogenic extended ADP (AADP) method

¹Section 3 builds on excerpts from the following published book chapter: "Charpentier Poncelet, A., Beylot, A., Muller, S., Villeneuve, J., Loubet, P., Laratte, B., & Sonnemann, G. (2021). Dissipation of minerals in Life Cycle Assessment, in: Pradel, M., Busato, G., Muller, S. (Eds.), Mineral Resources in Life Cycle Assessment. New Research Developments and Feedbacks from Private and Public Stakeholders. EcoSD Annual Workshop 2020. Presses des Mines, Paris, pp. 23–35.

considers anthropogenic stocks to be part of the global stock of mineral resources in addition to ultimate reserves (Schneider et al., 2015, 2011). However, it may be seen as inconsistent since the use of extraction rates in the numerator of the characterization factors (CF) actually transfers minerals from the geological to the anthropogenic stock, and therefore do not lead to the depletion of accessible stocks (Berger et al., 2020; Sonderegger et al., 2020)..

The idea that the dissipation, or dilution, of mineral resources is the relevant issue when addressing resource use has been around for nearly two decades (Stewart and Weidema, 2005; van Oers et al., 2002). Until recently, no concrete implementation of dissipation had been made applicable, although the need for an update of the indicator for mineral resource use was raised during the pilot phase of the PEF (2013-2018). Initial conceptual developments were advanced as part of the Organization Environmental Footprint Sector Rules for copper production (European Commission, 2018b, 2015) and the feasibility of implementing dissipative flows in the LCI was evaluated in a seminal report by the Joint Research Centre of the European Commission (EC-JRC) (Zampori and Sala, 2017).

Given the important functions that mineral resources hold for humans in the economy, the dissipation of mineral resources, rather than their extraction, has gained increasing interest when assessing the damage of mineral resource use on the AoP Natural Resources (Berger et al., 2020; Beylot et al., 2020; Zampori and Sala, 2017). An extensive literature review led by Beylot et al. (2020b) revealed that an increasing amount of studies on the national or global scale (statistics or material flow analysis (MFA) studies) and at the product scale (LCA studies) have addressed the concept of resource dissipation (or losses). Indeed, many researchers in the MFA and LCA fields have suggested that the real consumption of mineral resources is due to dissipation and hence should be addressed (Berger et al., 2020; Gössling-Reisemann, 2008; Helbig et al., 2020; Schulze et al., 2020; Stewart and Weidema, 2005; Vadenbo et al., 2014; van Oers et al., 2002; van Oers and Guinée, 2016; Zampori and Sala, 2017; Zimmermann and Gößling-Reisemann, 2013, 2015). In particular, the Task force mineral resources of the Life Cycle Initiative calls for the integration of the concept of dissipative resource use in developing future methods (Berger et al., 2020). Yet, developments are needed in both LCI and LCIA for this to become feasible (Beylot et al., 2020).

1.4 Objectives of the thesis

The aim of this thesis is to provide an operational LCIA method to account for the dissipation of mineral resources in the AoP natural resources. The method should be usable by LCA practitioners wanting to account for the impacts of dissipation in their studies, complementarily to impact mechanisms concerning mineral resource use. Therefore, the overarching question to this thesis is:

“Can life cycle impact assessment methods be developed to assess the impacts of the dissipation of mineral resources on the area of protection natural resources, in a complementary way to other impact assessment methods?”

The following sub-objectives serve to achieve the main objectives of the thesis:

- a) Identify impact pathways for mineral resource use and their linkage to the safeguard subject for the area of protection natural resources proposed by the Life Cycle Initiative’s taskforce on mineral resources.
- b) Identify challenges and concepts to account for the dissipation of mineral resources and develop a conceptual framework to consider it in life cycle assessment.
- c) Generate dynamic MFA data needed to develop characterization factors to account for the dissipation of mineral resources in life cycle assessment.
- d) Develop life cycle impact assessment methods and their respective characterization factors that can be applied in LCA studies.
- e) Demonstrate the applicability of the developed characterization factors with a case study.

Each sub-objective is addressed by a chapter of the thesis, as described hereafter. Their articulation within the manuscript is depicted in Figure 1-3.

After the introduction (**Chapter 1**), **Chapter 2** provides a theoretical background within which impact pathways and associated impact assessment methods can be linked to the AoP natural resources. An extensive definition of mineral resources and of their value for different users, adapted to the context of life cycle approaches, is proposed. Cultural perspectives (egalitarians, hierarchists and individualists) are detailed. Each pursue different socio-economic objectives with different means. Eleven impact pathways could be identified, out of which eight are most relevant to egalitarians, nine to hierarchists, and three to individualists. These are linked to endpoint damage on the AoP natural resources, and discussion provides some potential steps forward toward endpoint impact assessment on the AoP.

Chapter 3 provides a state of the art for dissipation of mineral resources in LCA, and identifies two potential ways forward to account for the dissipation of mineral resources in LCA based on dynamic MFA data. Option 1 consists in updating existing LCI to account for dissipative flows and applying adapted CFs to assess their impacts. Option 2 is to develop CFs that include dissipation profiles for different mineral resources and apply them directly to extraction flows of the LCI.

Chapter 4 allows obtaining dynamic MFA results for 61 metals, building on the MaTrace dissipation model. It includes a large data collection stage in which process yields and end use distributions are compiled for all of the studied metals. Uncertainty evaluation is implemented in the dataset and

model, enabling to compute a 95% confidence interval on the key result of the model. Another result from this chapter is a transparent, machine readable dataset made publicly available, which may be reused for other studies in the industrial ecology or LCA communities.

Chapter 5 builds on the second option outlined in chapter 3, and proposes two methods that allow assessing the midpoint impacts due to dissipative flows of mineral resources, which can be applied to extraction flows in the LCI. The first method, called average dissipation rate (ADR), is proposed as a standalone indicator which provides indications on how fast different metals are dissipated after they have been extracted from the environment. The second one, called lost potential service time (ADR), assesses the lost opportunity to make use of dissipated resources over time, due to dissipation. Moreover, endpoint CFs are proposed in order to compare between the values of different mineral resources for humans. Midpoint CFs are computed for 61 metals based on dynamic MFA results obtained in Chapter 4, and endpoint CFs, based on a price-based index.

Chapter 6 presents an application study for the computed CFs for the ADR and LPST methods. For this evaluation, the elementary flows of 45 metals are characterized for 5 999 market data sets from a widespread LCI database, grouped by section of economic activity. The impact assessment results are compared with those for popular characterization models: the abiotic depletion potential (ADP) method and the ReCiPe 2016 method. We also directly compare CFs between these different LCIA methods.

Finally, a general discussion on the main outcomes of the thesis is provided in in **Chapter 7**. The developed ADR and LPST methods are evaluated against five scientific criteria and perspectives for further method developments are identified. Furthermore, the ways forward for a more comprehensive assessment of the impacts of mineral resource use on the AoP natural resources are discussed, including perspectives for dissipation-oriented approaches. Finally, a general conclusion shows how research questions have been answered, and perspectives for future research are identified.

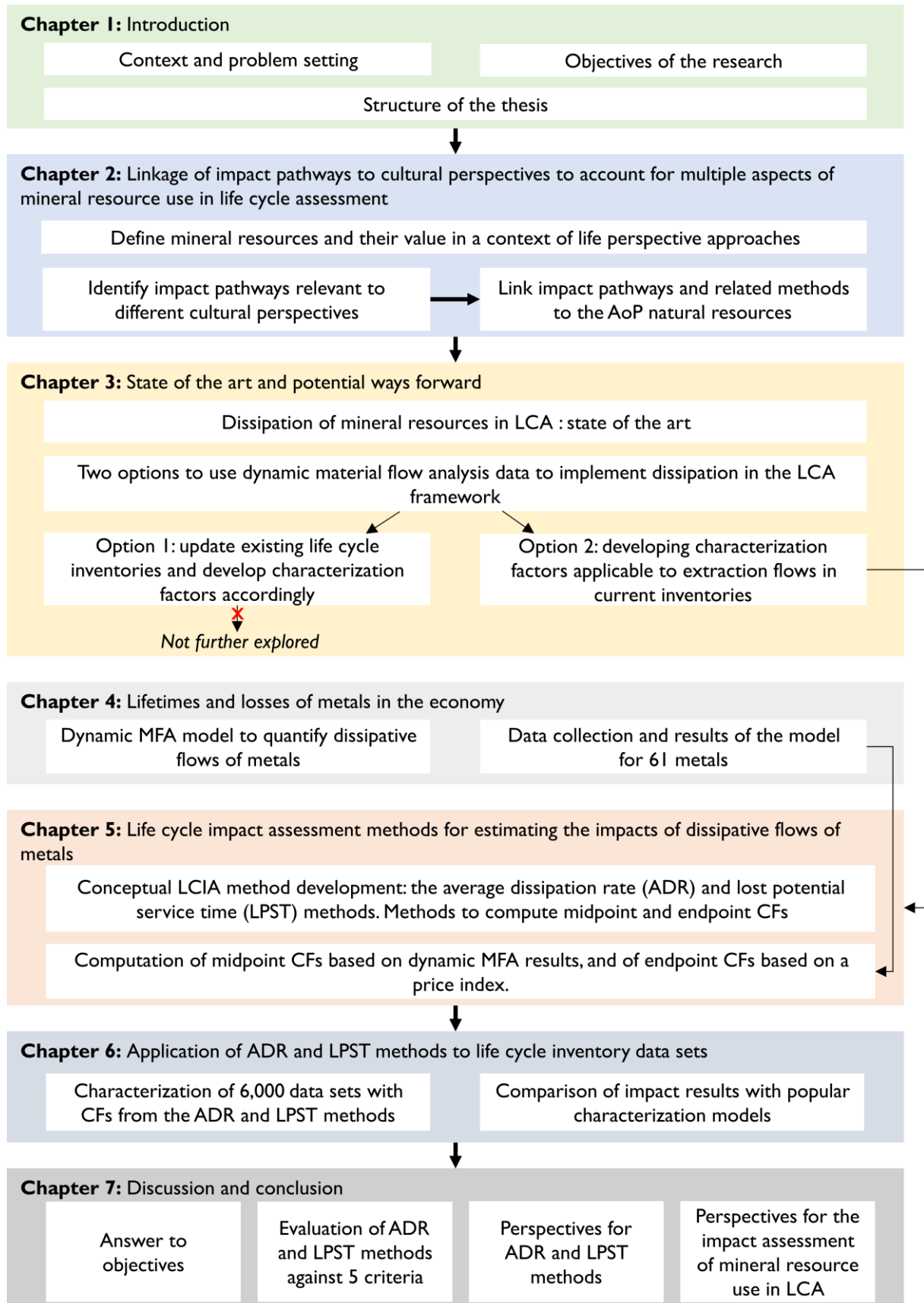


Figure 1-3. Structure of the thesis

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Chapter 2. Linkage of impact pathways to cultural perspectives to account for multiple aspects of mineral resource use in life cycle assessment

This chapter aims at proposing a definition of mineral resources and of their value from a life cycle perspective building on existing literature, as well as an analytical framework allowing to classify multiple potential impact pathways to the AoP natural resources under different cultural perspectives. Important advances have been made to define the multiple impact pathways relating mineral resource use to the area of protection (AoP) natural resources in life cycle assessment (LCA). Yet, the link between stakeholders' interests and the aspects relevant to resource use as addressed by existing impact assessment methods has so far only marginally been explored. This chapter proposes to go beyond the case-specific determination of stakeholders' interests (and the associated selection of impact assessment method) by defining multiple groups of different values based on cultural perspectives, in order to determine the corresponding relevant impact pathways and assessment methods.

Relying on the Cultural Theory and related potential development scenarios, we identify socio-economic objectives and resource management strategies that fit the egalitarian, individualist and hierarchist perspectives. Our analysis reveals that different aspects of resource use may be most relevant to assess for each perspective since they pursue different socio-economic objectives. Egalitarians are expected to prioritize the long-term availability of geological stocks for future generations by keeping extraction flows to a minimum to reach global sufficiency, and individualists, to safeguard their short-term accessibility to resources by managing their supply risk. Hierarchists are likely to aim to maximize the value obtained from resources globally, and could thus focus on addressing dissipative flows. Building on this analysis, we provide a proposal for a more holistic assessment of the impacts linked to mineral resource use using existing LCIA methods, and identify ways forward for method developments to come.

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2.1 Introduction

2.1.1 Context

Life cycle assessment (LCA) is a well-suited method to estimate the environmental impacts of products and services. Multiple impacts pathways link life cycle inventory (LCI) data (extraction and emission flows) with midpoint impact categories, which may then be translated into endpoint damage on three so-called areas of protection (AoP): human health, natural environment (or ecosystem quality), and natural resources (European Commission et al., 2010). The scope and definition of the AoP natural resources has been increasingly studied in the past years (Dewulf et al., 2015; Drielsma et al., 2016b; Sonderegger et al., 2017; Sonnemann et al., 2015). Notably, the Life Cycle Initiative, regrouping numerous LCA scientists and experts (Berger et al., 2019; Frischknecht and Joliet, 2016), worked on improving the definition of the AoP. Recently, its Taskforce on mineral resources (henceforth, "MR taskforce") completed an extensive review of all of the life cycle impact assessment (LCIA) methods addressing mineral resource use (Sonderegger et al., 2020). The authors identified several aspects related to mineral resources which may be relevant to consider within the AoP natural resources: depletion, dissipation, the changing quality of mineral resources and its consequences, the economic externalities of their extraction, the consumption of exergy or emergy embedded in resources, as well as availability or accessibility issues due to physico-economic scarcity, geopolitics and socio-economic aspects of supply risk (Berger et al., 2020; Sonderegger et al., 2020). Furthermore, they defined the safeguard subject for mineral resources in the AoP as *"the potential to make use of the value that mineral resources can hold for humans in the technosphere"* and have identified the damage as *"the reduction or loss of this potential caused by human activity"* (Berger et al., 2020). The authors also identified seven potential questions a practitioner may want to answer to related to different resource aspects, and made recommendations regarding the most suitable LCIA methods available to address each of these questions.

2.1.2 Challenges and objectives

Addressing the multi-faceted aspects related to mineral resources altogether and structuring the impact assessment in the AoP remains challenging. While the MR taskforce determined the aforementioned questions and recommended appropriate LCIA methods addressing them, they did not determine how to address multiple aspects associated with mineral resource use altogether. Moreover, most of the methods suggested or recommended by the MR taskforce quantify midpoint impacts rather than endpoint damage, suggesting that identifying and measuring the endpoint damage is uneasy. An underlying problem seems to lie within the definition of resources, consistently referring to their value for humans, with no specification of which value, nor which humans, are referred to. A

review of existing definitions by Beylot et al. (2020b) showed that, in the common anthropocentric perspective, resources have typically been defined based on their intrinsic value or utility for humans, since their functions answer specific needs or more generally contribute to human well-being. The definition of mineral resources as proposed by the MR taskforce makes no exception. In addition, the related safeguard subject refers to their accessibility for humans globally rather than to their intrinsic value in the environment (Berger et al., 2020; Schulze et al., 2020). Yet, while resources are defined as being of utility or of value to humans *in general*, or globally, they are in fact only beneficial to actors accessing and making use of the value they have *for them*. This was made evident in the recent enthusiasm for critical materials assessments (European Commission, 2020; Graedel et al., 2015; Sonderegger et al., 2015) and relatable risk-based assessment methods developed for LCA (Bach et al., 2019, 2016; Cimprich et al., 2019, 2018; Gemechu et al., 2016).

In this light, the safeguard subject as defined by the MR taskforce may be interpreted differently depending on which group of humans is referred to (both regionally and temporally) as well as which are their objectives, leaving a wide margin to subjectivity when assessing the impacts of mineral resource use on the AoP natural resources: What is the value of resources? Who should have access to resources and their value? How should they be managed through space and time? Answering such questions inherently involves value judgements. Consequently, the impact mechanisms relevant to practitioners also depend on what they value. For such reasons, the MR taskforce recommended methods that may be used by LCA practitioners depending on the questions they wish to address. Yet, while LCA is a value-based tool implying decisions on what is to be safeguarded in space and time, the link between the problematic to be addressed during impact assessment and the often implicit value choices and assumptions undermining each LCIA method's model are not self-evident (Finnveden, 1997; Hellweg et al., 2003). Moreover, it is arguably of crucial importance to align the impact assessment of mineral resource use with objectives, since the *potential to make use of the value of resources* inherently depends on the planning of the mineral supply and resource management accordingly with objectives such as those embodied in UN sustainable development goals (SDG) (Ali et al., 2017; Schandl et al., 2016; UNEP, 2017; Wackernagel et al., 2021). For instance, the Swiss ecological scarcity method integrates policy objectives in its impact assessment model (Frischknecht and Büsser Knöpfel, 2013).

Hofstetter (1998) stated that all modelling choices made in LCA should be consistent with a single world view, and defended that the Cultural Theory (Thompson et al., 1990) is relevant for such modelling decisions. The widely used ReCiPe method (Goedkoop et al., 2013; Huijbregts et al., 2017) and the underlying eco-indicator99 method (Goedkoop and Spriensma, 2001) build on cultural perspectives as defined in the Cultural Theory. These cultural perspectives, or archetypes, represent

different lenses through which humans may see the world and value things, nature and people around them or afar in space and time (Hofstetter, 1998). Out of five perspectives, the individualist, egalitarian and hierarchist ones are particularly fit for the LCA decision making context (Hofstetter, 1998). In the ReCiPe and eco-indicator99 methods, the selection of impact methods to assess the impacts of mineral resource use is made easier for the practitioner, since subjective assumptions and choices underlying the selection of relevant impact mechanisms and time horizons are attributed to specified cultural perspectives. Yet again, a single impact pathway is proposed to account for the impacts of mineral resource use in these methods, providing a limited representativeness of the cultural perspective for the AoP natural resources.

The main objectives of this work are to define mineral resources and their value in the context of life cycle approaches, to identify resource management strategies in line with different socio-economic objectives proper to the individualist, egalitarian and hierarchist perspectives, and to identify and link relevant impact pathways to the AoP natural resources under these three perspectives. To address these challenges, we first propose a comprehensive definition of the value of mineral resources relevant to life cycle perspective approaches such as LCA, and identify the beneficiaries of this value (section 2.2). Secondly, building on the notion that different resource management strategies may be used to pursue different social and economic objectives respective to different cultural perspectives, we propose a linkage between cultural perspectives and concrete strategies (section 2.3). The developments proposed in section 2.3 allow identifying impact mechanisms that may be most relevant to each perspective (section 2.4). As a result, we come up with a proposal on how impact pathways and the corresponding LCIA methods can be sorted based on the cultural perspective(s) that they best represent (section 2.5). In this way, we provide initial guidelines to address mineral resource use in a more comprehensive way in LCA under different cultural perspectives. A discussion and depictions of our key findings are provided in section 2.6.

2.2 Mineral resources and their value

The MR taskforce defined mineral resources as "*chemical elements (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand), as embedded in a natural or anthropogenic stock, that can hold value for humans to be made use of in the technosphere*" (Berger et al., 2020). These correspond to the resources identified within box A of Figure 2-, which are studied in this chapter. A complementary description of the different mineral resources identified in the figure is provided in Annex A.

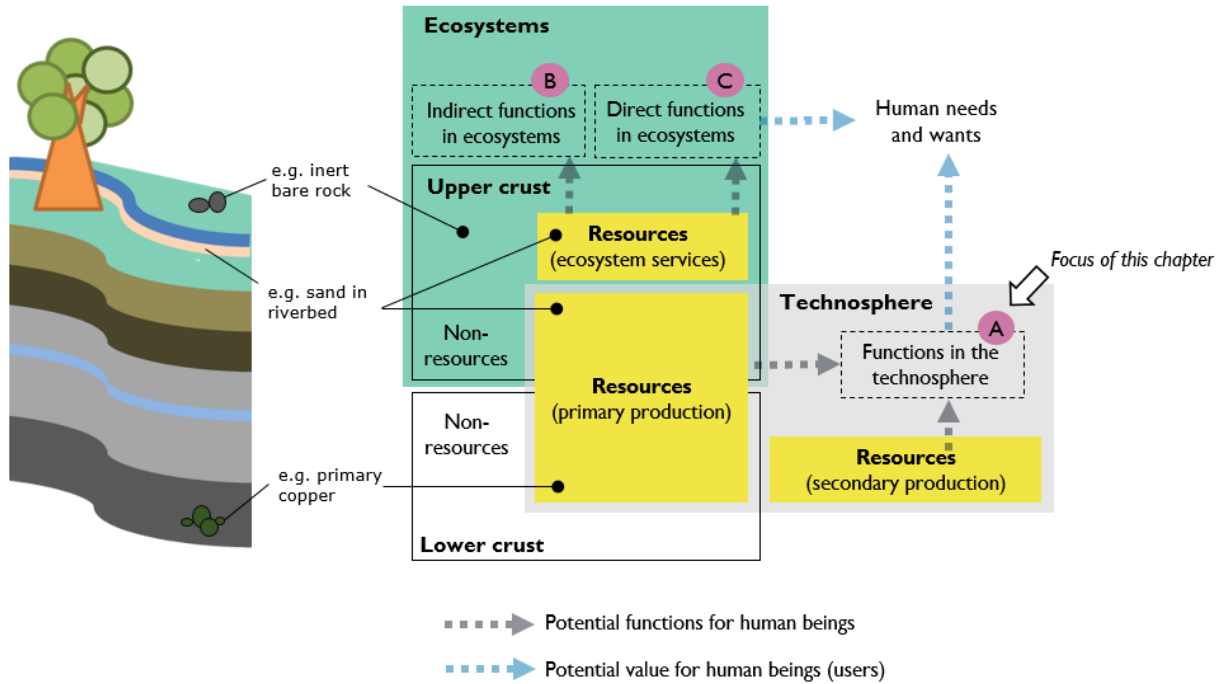


Figure 2-1. Identification of mineral resources providing functions in the technosphere (A) and ecosystems (B and C)

The potential functions in the technosphere may be obtained through current or future transformation activities in the economy and have a potential value for human beings at some point in time. From the classic utility theory upon which are based modern economics, two different meanings can be distinguished for the word "value": "[it] *sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called value in use; the other, value in exchange*" (Stigler, 1950, citing Smith, 1937). Generally, only does a *value in use* obtained through human activities has an *exchange value*, although some *use values* are also provided directly by nature (Marx, 1867). The former refers to products and services obtained in the economy, while the latter refer to direct functions obtained from ecosystems (i.e. ecosystem services).

It is thus useful to distinguish between the economic *exchange value* and the *use value* of mineral resources. We henceforth refer to the exchange value as an *economic value*, and retain the terminology for *use value*. In this chapter, the use value specifically refers to the experiential value that may be accredited to the functions of final products when the final consumer makes use of them. For an exhaustive coverage of what the final products may include, we refer readers to the description of the *household's actual consumption*, resulting from the expenditure of households, governments and non-profit institutions serving households (NPISHs), as proposed by Lequiller and Blades (2007). Put briefly, final consumption includes all final products and services whose use values fulfill human needs

and wants, such as household appliances, public and private infrastructure, etc. The economic value is usually represented by the price obtained in exchange of a good on a market; this economic value may be reinvested in other capital (e.g. infrastructure) or distributed amongst different stakeholders (e.g. to a state through taxes, to employees through salaries, to shareholders, etc.).

2.2.1 Value chain of mineral resources

In general, the different mineral resources are found in nature in low concentrations, and deposits containing higher concentrations are geographically dispersed (Blomsma and Tennant, 2020). Therefore, they require more or less intensive transformation before they can provide use values to humans. Primary resources are extracted, beneficiated and refined in most cases, then usually sold to a third party for further transformation. The economic value of these primary mineral resources, i.e. their rent, is typically shared between the extractive industries and the resource's owner (often a nation) through various taxing schemes (Bulearca et al., 2012). Refined mineral resources are manufactured into more complex materials (e.g. alloys) and components (e.g. hard disk drives), which themselves only provide a use value as part of broader product systems (e.g. aircrafts and computers) (Blomsma and Tennant, 2020; Greenfield and Graedel, 2013). Like primary (and secondary) resources, intermediate goods may be traded for their economic value, but have no use value for final consumers on their own. The transformation of mineral resources into materials and semi-products provide the successive intermediaries with new properties, generally increasing their economic value.

The economic value generated along value chains does not represent the finality of value chains: they are meant to supply consumers with final products whose use value answer their needs and wants. It is therefore the demand for use values of products that drives production systems, and eventually allows organizations to capitalize on the surplus economic value generated along supply chains. Thus, as the last step of the value chain, products and services are purchased by final consumers in order to fulfil their needs and wants. The economic value of products generally reflect the final consumers' willingness to pay for them, based on the perceived use value they may get from them in their respective context (Le Gall-Ely, 2009). Henceforth, we distinguish between the economic value of the mineral natural capital (accessed through exploration, extraction and refining processes), the economic value of supply chains (e.g. employment, rents, taxes, financial capital, etc.), and use values. Figure 2-2 illustrates examples of potential supply chains and applications making use of the mineral chalcopyrite and its elemental constituents regardless of their economic feasibility.

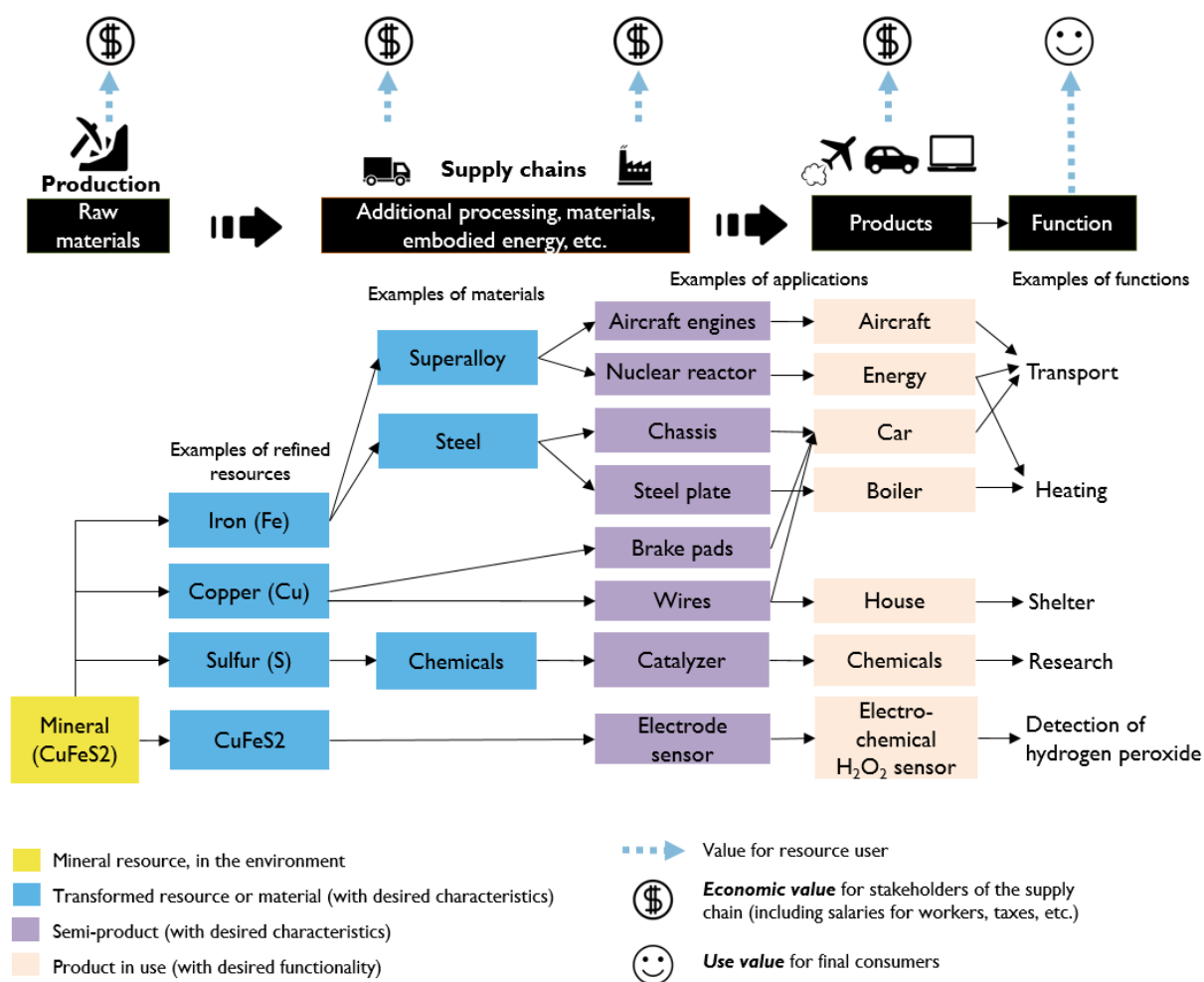


Figure 2-2. Potential supply chains making use of the mineral chalcopyrite (CuFeS_2) to generate economic and use values

One same mineral resource may be used in various supply chains, each of them generating different values for potentially different users. The quality of the resource may have implications on which applications it is fit for (Stewart and Weidema, 2005). For example, while chalcopyrite is generally economically extracted for its copper content, some applications could make use of the mineral as such, such as sensor electrodes for the detection of natural hydrogen peroxide (Wang et al., 2018). The elements it contains can be used both as pure single elements (e.g. copper in electrical wires), or as composite materials (e.g. steel used in a boiler). In addition to the multiple potential states that may be valued for one same mineral, multiple characteristics could be of use for each of them. For instance, pure copper can be used for its conductivity as part of wires or electronic devices, or for its resistance to corrosion as part of copper pipes. The functions of final products result from the characteristics of resources or materials they are composed of, of the labor put to contribution in their manufacturing including energy, as well as the different capitals (i.e. manufactured, human, social and financial capitals) that are required to transform them along value chains. In LCA studies, functions are typically

reported as the functional unit of a product or process, and do not refer to economic values nor use values they generate.

2.2.2 Beneficiaries of the value of mineral resources

The physical availability of geological reserves of mineral resources does not guarantee their technico-economic accessibility for humans (Drielsma et al., 2016b), and even less so their accessibility for one specific group of humans. Indeed, the economic value held by primary resources is only accessible to those that can legally operate locally or abroad while having the indispensable pre-accumulated capitals to do so. These include the financial capital required to invest in new projects (e.g. exploration and building infrastructure), the manufacturing capital required for extraction and transformation, the human capital in the form of knowledge and skills (e.g. breveted metallurgical process and trained personnel), and the social capital (including favorable geopolitical relationships and the social license to operate locally). For instance, environmental, social and governance risks may have an incidence on which resources are accessible in different regions, as such risks can disrupt the opportunities to explore for ore bodies and the feasibility of subsequent mining operations (Ali et al., 2017; Kerr, 2014; Lèbre et al., 2019; Northey et al., 2018). Generally, the main stakeholders for the economic value of primary raw materials are nations possessing resources, as well as extractive industries aiming to generate socio-economic benefits from extracting and processing them. This economic value may be an important support to a territory's socio-economic activities and to its development (EITI, 2019; IIED, 2002; Wall and Pelon, 2011). While Graedel and Cao (2010) found out that the production and processing of primary resources is rather independent from nations' development, it can be observed that most of the world's largest mining companies operating worldwide are of Australian, British, American, Canadian, Russian, South African, Chinese or Hong Kong ascendance (PwC, 2019), suggesting that there is a relatively high concentration of capital shared between these organizations and their respective stakeholders. These organizations all emanate from relatively advanced developing countries or developed countries with a long history of mining activities, except for China which has quickly caught up in this millennium, largely relying on its important reserves (cf. USGS, 2020).

Like extractive industries, the transformation industries also generate socio-economic benefits from their activities. Some economies are specialized in generating surplus economic value from the transformation of resources into products along global value chains, such as those in eastern Asia, Western and northern Europe and the US (The World Bank, 2020). In general, it appears that developed nations and organizations within, which rely on extensive pre-accumulated capitals as well as favorable geopolitical relationships, are more competitive than low- and mid-income countries, and

therefore have a greater access to resources traded on international markets (Wackernagel et al., 2021). Coherently, Graedel and Cao (2010) showed that there is a rather high correlation between the level of development and of competitiveness of nations, and the intensity of their resource transformation and use.

The concentration of economic value generation from both natural capital and transformation activities within developed countries leads to an increased accessibility to the use value of final products (including public and private infrastructure) for organizations and citizens of these same countries. Indeed, they generate more GDP per capita, and citizens within generally have a greater purchasing power than those of low- and mid-income countries (UNEP, 2017, 2016). For instance, Nakajima et al. (2018) and Watari et al. (2020) showed that the consumption and accumulation of metals is much larger in developed countries and in China than in other countries. China may indeed be considered to be on par with developed countries in terms of industrial potential given the current competitiveness of its supply chains, the extent of its infrastructure, and its increasingly important involvement in global economic activities in the past two decades (The World Bank, 2020; World Economic Forum, 2019).

2.3 Resource management strategies in line with cultural perspectives

The current trends of the accessibility of resources and their value as described in the previous section may be desirable for some, and less for others. In this section, we propose plausible resource management strategies in line with socio-economic objectives suitable to the individualist, hierarchist and egalitarian perspectives. Their respective objectives and corresponding resource management strategies are theorized following the Cultural Theory as interpreted by (Hofstetter, 1998), established future world scenarios of the UN Environmental Programme (UNEP, 2007), and complementary literature. Four 'GEO-4' scenarios have been defined: Markets First, Policy First, Sustainability First, and Security First, as presented in the chapter 9 of the Global Environment Outlook (GEO) report (UNEP, 2007). Each scenario represents a potential avenue of how current social, economic and environmental trends could unfold along different development paths depending on different policies and societal choices. In the Markets First scenario, international trade is deregulated in order to pursue a flourishing global economy, giving most place to the private sectors. The similar *Yale Market World* scenario (Elshkaki et al., 2018) implies an increasingly widespread use of resources whose deposits are not even distributed geographically. In the Sustainability First scenario, public and private organizations and nations cooperate to address social and environmental concerns at the global scale. This scenario entails an increase in resource consumption for developing countries to build up their infrastructure (Elshkaki et al., 2018; UNEP, 2017). In the Policy First scenario, similar goals to the

Sustainability First scenario are pursued, but are enforced by highly centralized policies rather than emerging from a natural cooperation between the different actors. Markets are heavily regulated as to ensure that goods and services are not provided at the expense of key ecosystem services and overexploitation of non-renewable resources. In the Security First scenario, nations prioritize their own security and economy with small regards to other nations. More details on the four scenarios are provided in section A.2.3 (Annex A).

In the next three subsections, we further interpret the egalitarian, individualist and hierarchist perspectives with regards to which GEO-4 scenario(s) might appeal to them the most given the socio-economic goals they are inclined to pursue, and consequently which resource management strategy they may tend to prioritize. The perspectives are attributed to either organizations, nations or global scales. Figure 2-3 presents the key determinants for the following analysis. The results of the analysis are summarized in Table 2-1. Complementary information and justifications underlying the rationale for linking specific resource management strategies to cultural perspectives are provided in section A.3 (Annex A).

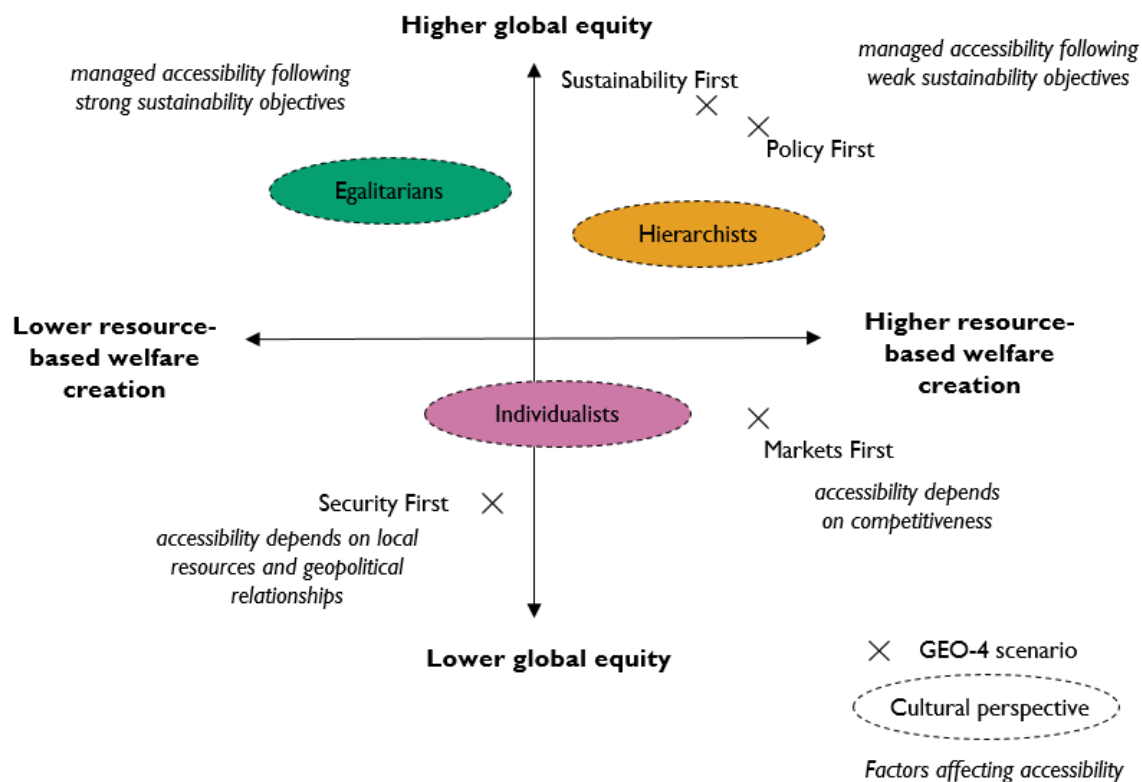


Figure 2-3. GEO-4 scenarios and cultural perspectives distributed over four quadrants with regards to the expected interregional equity in the accessibility to resources and the global resource-based welfare creation

The placement of elements on the graph are only indicative in order to compare between scenarios and perspectives. They do not refer to quantified metrics. The hierarchist perspective is best embodied

in the Policy First and Sustainability First scenarios; the individualist perspective, in the Security First or Markets First scenarios (depending on upmost local interests: security or commerce); and egalitarian perspective, in none of the scenarios.

2.3.1 Egalitarians

Egalitarians value the long term over the short term, and are mostly interested in the global and long-term survival of the human population, with a minimal amount of burden shifting to future generations (Hofstetter, 1998; Huijbregts et al., 2017). They also view ecosystems as fragile and sensible to human interventions (Mamadouh, 1999; Thompson et al., 1990), and hence could argue that maintaining their integrity is primordial to support human life in the long run as they cannot be replaced (see Norton, 2002). Moreover, they are risk-adverse and view resources as prone to depletion (Hofstetter, 1998), accordingly with the pessimistic fixed stock paradigm (Tilton, 1996). Thus, the development scenario for egalitarians could align on strong sustainability principles, entailing the protection of irreplaceable ecological functions that contribute to human welfare, i.e. deemed to be critical natural capital (Ekins et al., 2003; Pelenc and Ballet, 2015). Hofstetter also noted that the egalitarian perspective closely aligns on strong sustainability principles (cf. Hofstetter, 1998, p. 68-69).

While we estimate the egalitarian strategy would focus on preserving the integrity of ecosystems rather than on a concerted mineral resources management, it can be expected that global social equity would be at the heart of an egalitarian resource management strategy. Therefore, we consider that egalitarians will favor a parsimonious access to resources combined with an efficient use in order to meet human needs globally, i.e. aiming for global sufficiency rather than local welfare. Hence, egalitarians may opt for a resource management strategy that reduces present consumption in the high-income countries, and favor an equitable access to resources required for the global long-term sufficiency in developing ones (cf. Figure A-4 in Annex A). Accordingly, the political strategy archetype for egalitarians could be branded *social justice through sufficiency*.

2.3.2 Individualists

Individualists position themselves before others, both in space and time (Hofstetter, 1998). Thus, they are likely to aim for a maximal profitability for the current generation and locally. They are optimistic about technological developments and the capacity of future generations to adapt, and believe resources to be abundant (Hofstetter, 1998). Therefore, securing the organization's or nation's welfare and maximizing its profits in the short or midterm is expected to be of upmost importance to individualists.

At the organizational or national scale, individualists could incline to the Security First or Markets First scenarios depending on their upmost interests. If projected at the global scale, it can be estimated that individualists would aim to generate high resource-based welfare for the current generation. Still, one should note that the individualist perspective is inherently hardly compatible with global assessments as the interests of each subgroup are self-centered and primarily valued over that of others. We therefore estimate that individualists would most favor management practices that secure their own resource supply by means of economic and technological competitiveness, and that favor trade agreements, stockpiling, geopolitical relations, lobbying, etc. It can be observed that the individualist take on resource use is the most related to the current patterns on the accessibility to resources presented in section 2.2.2. Therefore, the political strategy archetype for individualists is branded *business as usual*.

2.3.3 Hierarchists

In a way, hierarchists may be thought of as a middle ground between the egalitarian and the individualist perspectives. They favor a fair and positive outcome for both current and future generations globally, and are optimistic on technological adaptation to sustain human welfare (Hofstetter, 1998). Hence, it can be estimated that hierarchists would attempt to maintain a balance between the development of the manufactured environment and environmental protection that tend to increase human welfare through space and time, i.e. by promoting the development of lower income countries while sustaining welfare in industrialized countries. Such development strategy generally aligns with weak sustainability principles, which contrasts with strong sustainability as it promotes technological progress as a means for human development and welfare, based on the assumption that natural capital can essentially be substituted with manufactured capital (Bullock, 2017; Ekins et al., 2003). Hofstetter also noted that the hierarchist perspective generally aligned with weak sustainability principles (cf. Hofstetter, 1998, p. 68-69). This perspective is most compatible with UNEP's Sustainability First and Policy First development scenarios, that generally embody the 17 sustainable development goals (SDGs) of the UN (UN, 2015, 2012). Pursuing a global socio-economic development is commonly in line with propositions of the UN (see e.g. UN, 2018), UNEP's International Resource Panel (IRP) (see e.g. UNEP, 2017; IRP, 2019) and the World Bank (see e.g. The World Bank, 2020). Coherently, UNEP's Life Cycle Initiative is currently working on integrating SDGs in the life cycle sustainability assessment framework (Life Cycle Initiative, 2020).

The political strategy archetype for hierarchists could thus be branded *social justice through cooperation and development*. Balancing short-term development goals such as SDGs with longer-term sustainability objectives requires to maintain a balance between the socio-economic benefits of the

production and consumption patterns and their environmental externalities. Strategies such as increasing resource productivity, circularity and efficiency are most typical when it is attempted to decouple resource consumption from human well-being. Nonetheless, it may imply to take smart decisions when weighting the benefits of these strategies with their own externalities (Allwood and Cullen, 2012; Pauliuk, 2018; Reuter et al., 2019).

Table 2-1. Egalitarian, individualist and hierarchist cultural perspectives and their respective relevant geographical scales and time scopes, as well as archetypal views of resource use and their corresponding socio-economic objectives, political strategy archetypes, and preferred resource management strategies.

| Cultural perspective archetype | Time horizon of interest (Hofstetter, 1998) | Geographical scope of interest | GEO-4 Scenario (UNEP, 2007) | Socio-economic objective | View of mineral resources (Adapted from Hofstetter, 1998) | Political strategy archetype | Resource management strategy |
|--------------------------------|---|--------------------------------|---|--|---|---|---|
| Egalitarian | Long term > short term | Global (Hofstetter, 1998) | Sustainability First (with an emphasis on environmental protection & sufficiency) | Equitable opportunities for future generations | Resources are depleting: they should be used with parsimony and their value should be preserved for future generations. | <i>Social justice through sufficiency</i> | Minimal consumption for global sufficiency, following strong sustainability principles |
| Individualist | Short term > long term | Organization | Security First or Markets First | Optimized opportunities for the organization | Resources are vital to the organization. Their access should be secured to maintain the activity. | <i>Business as usual: survival of the fittest</i> | Secure resource supply to sustain economic activity & increase competitiveness |
| | | National | Security First or Markets First | Optimized opportunities for the nation | Resources are vital to the nation. Their access should be secured to maintain the national economic activities. | <i>Business as usual: make my country great again</i> | Secure resource supply to sustain economic activity & increase competitiveness (e.g. strategic stockpiling & trade agreements), maximal consumption and efficiency - <i>Markets First</i> : Liberal policy & economic planning <i>Security First</i> : Prioritizing local industry & employment (including military) |
| | | Global | Markets first; however might be non-applicable: see section 2.3.2 | Optimized opportunities for the current generation | Resources are abundant and vital to the global economy. The access to resources should be secured to increase global economic activities. | <i>Business as usual</i> | Deregulation & free markets lead to increasingly widespread resource use |

| | | | | | | | |
|--------------------|---------------------------|--|--|---|---|---|--|
| Hierarchist | Short term = long term | Global (Local vs global outcomes) (Hofstetter, 1998) | Sustainability First or Policy First (with an emphasis on global welfare) | Enhanced opportunities for current & future generations | Resources are scarce but needed for sustainable development. They should be managed equitably globally and across generations. Use should be optimized to maximize global welfare. | <i>Social justice through cooperation and development</i> | Sustainable development through controlled resource use, improved technique and cooperation (e.g. circular economy & high resource productivity in developed countries, international cooperation to sustain socio-economic development of lower income countries) |
|--------------------|---------------------------|--|--|---|---|---|--|

2.4 Identification and classification of impact pathways

In this section, we systematically identify potential impact mechanisms and related LCIA methods addressing the impacts of mineral resource use on the AoP natural resources, building on the works of the MR taskforce (Berger et al., 2020; Sonderegger et al., 2020). We also propose complementary pathways associated with the potential to make use of the economic and use values under a life cycle perspective, as seen in section 2.2. We then set-up a method allowing to evaluate how well impact pathways fit cultural perspectives.

2.4.1 Existing impact pathways and associated LCIA methods

The MR taskforce has identified seven aspects of mineral resource use that may be addressed with existing LCIA methods, in addition to which the taskforce proposed that dissipation should be considered (Berger et al., 2020). From these, we identified seven impact pathways that are related to making use of the value of resources (impact pathways #1-7, presented in Figure 2-4 and Table 2-2 below). We considered that the pathway based on thermodynamics was not relevant. Moreover, we identified LCIA methods that may be relevant to assess each impact pathway, partly based on the recommendations of the MR taskforce. Each of these methods are described in section A.5 (Annex A).

Depletion (impact pathway #1) and dissipation (#6) both represent a reduction of the accessibility of mineral resources for future generations, that may reduce their potential to make use of the economic and use values of these resources. The former (#1) may be addressed with the ADP ultimate reserves method (van Oers et al., 2002; van Oers and Guinée, 2016) or the Crustal scarcity indicator (Arvidsson et al., 2020), and the latter (#6) with the Joint Research Centre's suggested approach (Beylot et al., 2021, 2020a), as well as the environmental dissipation potential (EDP) (van Oers et al., 2020), average dissipation rate (ADR) or lost potential service time (LPST) methods². The current over-extraction of mineral resources (impact pathway #2), the lowering ore quality (impact pathway #3), as well as the improper reinvestment of economic gains from the sale of mineral resources (impact pathway #4) may all lead to a reduced potential to make use of their economic value. Impact pathway #2 may be addressed with the Future Welfare Loss method addressing the lost economic value caused by unsustainable over-extraction (Huppertz et al., 2019); #3, with the surplus cost potential (SCP) method (Vieira et al., 2016); and #4, with the LIME2 endpoint method (Itsubo and Inaba, 2012). We considered the SCP method to be conceptually more relevant than the surplus ore potential (SOP) method (Vieira

² The ADR and LPST methods are developed in Chapter 5 of this thesis but kept here for consistency with the published article

et al., 2017) regarding developments proposed in this chapter. Finally, global or regional short-term supply risk (impact pathways #5 and #7, respectively) may affect current resource users' potential to make use of the economic and use values of mineral resources. Impact pathway #5 addresses the mid-term physico-economic scarcity of mineral resources (Berger et al., 2020), and may be addressed with the ADP economic reserves method (van Oers et al., 2002; van Oers and Guinée, 2016). Impact pathway #7 represents short-term supply risk linked with geopolitical and socio-economic aspects (Berger et al., 2020), which can be addressed at the national scale using the GeoPolRisk method (Cimprich et al., 2019, 2018; Gemechu et al., 2016) or at the global scale using the ESSENZ method (Bach et al., 2019, 2016).

2.4.2 Additional impact pathways

Accessing and using resources do not guarantee an optimal value creation amongst potential users over the life cycle of resources. The performance of resource-based welfare creation for their users can therefore be evaluated, as it influences the potential to make use of the economic and use values of mineral resources. It could include an evaluation of the current sustainability of the management and distribution of mineral resources amongst potential users (e.g. nations or supply chains) (impact pathway #8) and the efficiency of economic value creation along supply chains (#9), as well as the sustainability of the management and distribution of products amongst potential users (#10) and the efficiency of use value creation linked with the use of products for final consumers (#11). The assessment of impact pathways #8-11 should differ depending on each cultural perspective's socio-economic objectives. No existing LCIA method addresses these impact pathways. The eleven identified impact pathways are identified in Figure 2-4 in relation to the flows of resources or values they may apply to.

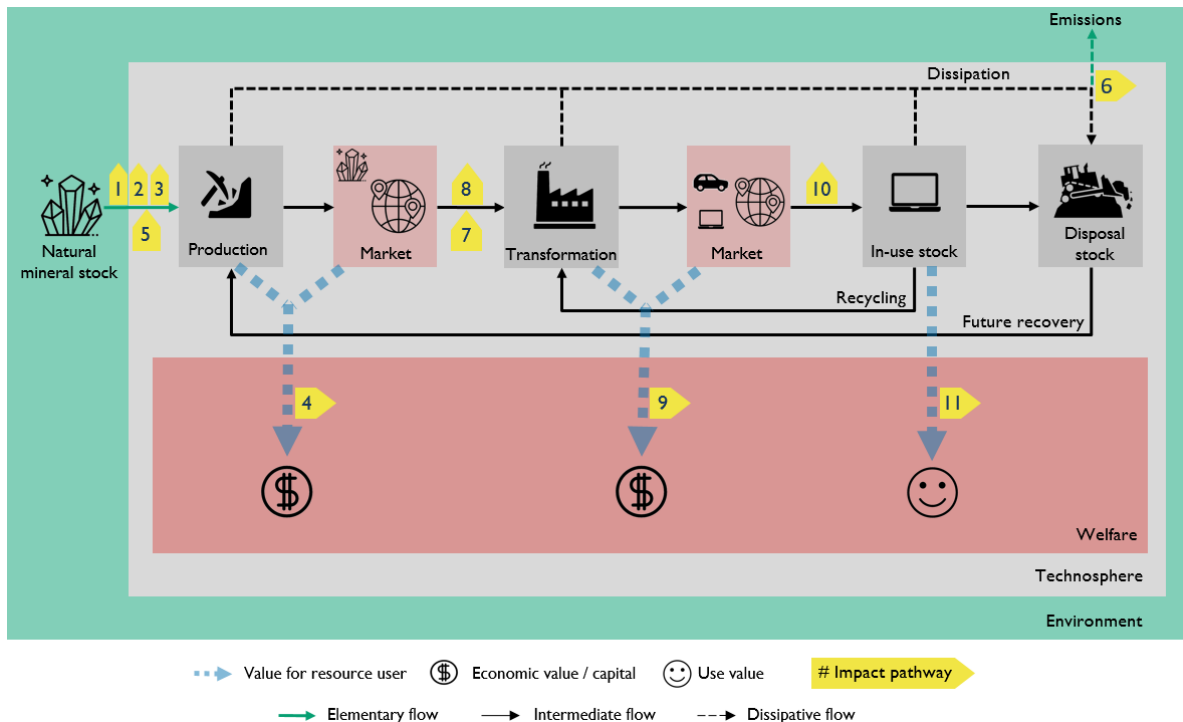


Figure 2-4. Resource stocks and flows and their economic values and use values along supply chains, as well as eleven potential impact pathways linked to the AoP natural resources

2.4.3 Classification method for linking impact pathways with cultural perspectives

The relevance of impact pathways to the different cultural perspectives is evaluated with three criteria: the geographical scope, the temporal scope, as well as the implicit beliefs (e.g. capacity of future generations to adapt) and associated response (resource management strategy) underlying the pathway. We evaluated relevance with a four-grade scale (none/very low, low, medium and high). For example, we evaluated long-term depletion not to be relevant to individualists because they are not interested in the long-term and tend to believe in their capacity to obtain ever more resources (or substitute depleted ones) thanks to technological solutions. The filled out evaluation grid is provided in section A.4 of Annex A. Impact pathways that are evaluated with a none/very low for at least one criteria were considered not to be most relevant for that cultural perspective. We here acknowledge that, while we attempted to remain as objective as possible, our evaluation may have involved some degree of subjectivity, which could be a limitation of our study. Results and analysis are described in the next section.

2.5 Linkage of impact pathways with cultural perspectives

In the three sub-sections below, we discuss impact pathways that were evaluated to be most relevant to each cultural perspective. Results are synthesized in Table 2-2 and Figure 2-5.

2.5.1 Impact pathways most relevant to egalitarians

Given their socio-economic objectives, egalitarians are more likely to esteem the use value of resources than their economic value generated along value chains. Nonetheless, they may look forward to an equitable distribution of the economic value generated from mineral natural capital globally (impact pathways #2 and 3). Moreover, given their aversion for risk-taking, their prioritization of equal opportunities for future generations, and their general alignment with strong sustainability principles, one aspect of mineral resource use that might appeal most to egalitarians is the depletion of long-term geological stocks (impact pathway #1). The total amount of resources that may be accessible in the long-term accordingly with the egalitarian perspective could tend to be seen as relatively small in comparison to the total geological availability (cf. discussion in Drielsma et al., 2016). Hence, the most precautionary depletion assessment could consider a small fraction of the crustal content as a proxy for the total long-term resource accessibility. As an endpoint damage, it could be attempted to quantify the lost potential use value for future generations related to the depletion of reserves. We here specify that egalitarians may only consider mineral resource use to be impactful to the AoP natural resources when it feeds product system's whose use values answer wants beyond sufficiency.

The wasteful use of resources, embodied in the concept of dissipation (cf. Beylot et al., 2020b; Zampori and Sala, 2017), could also be addressed by egalitarians as it may reduce the accessibility of resources for future generations (impact pathway #6). It would be relevant to take a long-term scope (e.g. 500 years) into account. The impact assessment of dissipative flows could thus be linked to a lost potential to make use of the value of resources over time, as proposed in the LPST method (Charpentier Poncelet et al., 2021c). Finally, egalitarians could aim to assess the unequal interregional accessibility to resources and their economic values and use values, resulting in an unequal accumulation of resources and capital, as briefly described in section 2.2.2 (impact pathways #8, 10 and 11).

2.5.2 Impact pathways most relevant to individualists

Given their socio-economic objectives and their focus on the short term, individualists are inclined to secure their own access to resources and to their values. Individualist organizations or nations may primarily attempt to secure their access to resources in order to generate economic value for their stakeholders (e.g. employees, shareholders, governments collecting taxes, etc.) and secure their accessibility to use values. If ever individualists are thought of at the global scale, it could be considered that they would attempt to maximize the current generation's welfare through uncontrolled production and consumption, with few regards to burden shifting to future generations. Therefore, it

seems that supply risk methods would be of utmost interest to individualists (impact pathways #5 and 7).

As individualists aim to maximize their welfare regardless of burden shifting to future generations, they may also aim to maximize the efficiency of resource use, i.e. by maximizing the economic value and use values that is generated with a limited amount of accessible resources at once (impact pathway #9 and 11). Although it was not suggested by the MR taskforce to address this specific aspect of resource use, the ESSENZ method also aims to measure the national resource efficiency. However, in the LCA context, measuring resource efficiency should rather be done at the product or organizational scales, since only these may be subject to LCA studies. No existing LCIA method measures resource efficiency at such scales. Still, some indication on resource efficiency can be calculated at the inventory level using existing approaches such as the Material Input per Service Unit (MIPS) (Liedtke et al., 2014). It could thus also be attempted to measure the efficiency of resource use of a product system in relation to the (economic) value generated by the functional unit in LCA.

Finally, the dissipation of mineral resources could potentially be a relevant aspect of the individualist assessment, especially for the scarcest or most critical ones. Nonetheless, individualists may consider that humans will be able to obtain ever more resources despite decreasing ore grades (e.g. for copper, see Gorman and Dzombak, 2020, and Kerr, 2014), thanks to exploration and technological development. They may therefore estimate that dissipation is not so much of an issue to deal with. Therefore, if ever dissipation is assessed under the individualist perspective, it could tend to only account for the short-term dissipation of mineral resources for which there is a local supply risk (e.g. critical materials). We stress that some attention should be spent on establishing coherent development scenario and timelines when setting impact mechanisms between dissipation and the AoP natural resources under this perspective, alike for other perspectives.

2.5.3 Impact pathways most relevant to hierarchists

Hierarchists believe in the contribution of the man-made environment to increase human welfare; yet, they also acknowledge resources to be rather scarce and should be used efficiently. Given their inclination for concerted solutions to pursue global development, they are likely to aim for a secured accessibility, efficient use, and equitable sharing of mineral resources with regards to sustainability objectives (cf. section 2.3.3). A continuous access to both primary and secondary resources is required to support economic activities in high-income economies as well as the socio-economic development of low or middle income countries (Bringezu, 2015; UNEP, 2017, 2016).

In this light, one aspect of mineral resource use evaluated to be highly important to hierarchists is dissipation (impact pathway #6). Indeed, dissipation goes against the global objective of a more circular

economy and increases the reliance on primary extraction, therefore putting pressure on geological stocks and compromising the accessibility of resources for future generations (Charpentier Poncelet et al., 2021b). Besides LCIA methods addressing dissipation, circularity indicators could also be relevant to consider as a positive image of dissipation methods (see e.g. Ellen MacArthur Foundation, 2019; Glogic et al., 2021; Niero and Kalbar, 2019). Moreover, given the general optimism of hierarchists regarding technological developments, they may consider that parts of the flows that have been made inaccessible today (e.g. resources stored in landfills or tailings) will become accessible again in within the timeframe relevant to their assessment (see e.g. Dewulf et al., 2021 and discussion of Charpentier Poncelet et al., 2021a). While such assumptions could possibly be implemented in dissipation-oriented methods, it should be kept in mind that impact assessment should provide signals and advices pointing towards sustainable technologies rather than assume it will happen by itself (Steen, 2006).

Regarding the accessibility to geological stocks, hierarchists could also be interested in the global mid-term supply risks linked with the depletion of mid-term reserves (impact pathway #5). For the endpoint damage assessment linked with potential accessibility issues (linked with dissipation and/or depletion), it can generally be expected that hierarchists would attempt to prevent the dissipation of resources that generate most economic and use values, that can hardly be substituted by other resources, and/or those most sensible to become depleted in the short to mid-term. Therefore, dissipation methods could be complemented with depletion, economic and/or substitution models to measure the endpoint damage on the AoP natural resources. For example, methods such as the anthropogenic extended ADP (AADP) (Schneider et al., 2015, 2011) could provide useful information on the global scarcity of resources to be matched with dissipation rates as measured with the ADR method.

Additionally, hierarchists would aim to generate sustainable value from the extraction (impact pathways #2-4), transformation and use of mineral resources (impact pathways #8-11). They could aim to increase the efficiency of resource use with regards to pursuing sustainability objectives in a cooperative way amongst organizations and nations, accordingly with the Sustainability First or the Policy First scenarios. For example, they could assess the sustainability of the sourcing of raw materials (see e.g. conflict-free minerals: Young, 2018), or the efficiency of the re-investment of the rents into local sustainable development (see e.g. the *Breaking New Ground: Mining, Minerals and Sustainable Development* report: IIED, 2002, and the Extractive Industry Transparency Initiative: EITI, 2019). Yet, addressing such aspects of resource use fall outside of the traditional LCA framework, and we leave these aspects open for discussion and future developments to come.

Table 2-2. Aspects of mineral resources and the related impact mechanisms most relevant to egalitarians, individualists and hierarchists

| Cultural perspective archetype | Relevant aspects of mineral resources | Question related to the impacts of mineral resource use (adapted from Berger et al., 2020) How do I quantify the... | Impacting flows (or other resource aspect, identified with an asterisk) | Potential impact mechanisms and damage | # impact pathways (fig. 4 and 5) | Potential LCIA methods (building on Berger et al., 2020) | Importance of the pathway with regards to the cultural perspective (low, medium, high) |
|--------------------------------|--|--|---|---|----------------------------------|--|--|
| Egalitarian | Preserve resources for future generations | ... contribution of a product system to the depletion of mineral resources? (Berger et al., 2020) | Extractive flows | Extraction leads to depletion, reducing the future accessibility of resources, resulting in a lost potential for future generations to make use of the use value of mineral resources | 1 | ADP ultimate reserves, Crustal scarcity indicator | High |
| | | ... contribution of a product system to the inaccessibility of mineral resources due to dissipation? | Dissipative flows & Hoarded and abandoned resources* | Dissipation (as well as hoarded and abandoned resources; cf. Dewulf et al., 2021) leads to the inaccessibility of resources, resulting in a lost potential to make use of the use value of the dissipated mineral resources | 6 | EDP, JRC suggested approach, ADR and LPST | Low-medium |
| | Efficiency of the use of resources with regards to pursuing global long-term sufficiency | ... contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering egalitarian socio-economic objectives? | Extractive flows | Current extraction leads to diminishing ore grades and increasing costs, resulting in a reduced potential to make use of the economic value of mineral resources | 3 | SCP | Low-medium |
| | | | Extractive flows | Current over-extraction of geological resources leads to lower total economic rent over time, resulting in a lost potential to make use of the economic value of mineral resources | 2 | Future Welfare Loss | Low-medium |
| | | | Inefficient resource use with regards to egalitarian socio-economic objectives* | Unequitable distribution of mineral resources and products, resulting in a lost potential for other potential users to make use of the economic value and use values of mineral resources | 8, 10, 11 | N/A | 8, 11: Medium 10: Low-medium |

| | | | | | | | |
|----------------------|---|--|---|--|-------|--|---|
| Individualist | Continuous accessibility to resources (organizational, national or global) | ... potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects? (Berger et al., 2020) | Supply disruption/ supply risk* | Supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic values of resources (also use values at regional or national scale) | 7 | Country or organizational level: GeoPolRisk Global level : ESSENZ | High |
| | Maximal supply & economic activity for current generation (global) | ... potential availability issues for a product system related to mid-term physico-economic scarcity of mineral resources? (Berger et al., 2020) | Supply disruption/ supply risk* | Supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic and use values of mineral resources | 5 | ADP economic reserves (However, mid-term assessment according to MR taskforce) | Low (if global scope deemed relevant) |
| | Efficiency of the use of resources with regards to local short-term welfare | ... contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering individualist socio-economic objectives? | Inefficient resource use with regards to individualist socio-economic objectives* | Inefficient resource use limits the total amount of welfare generated for the current generation, resulting in a lost potential to make use of the economic and use values of mineral resources | 9, 11 | N/A | 9: Low at global scale, medium at national scale, high at organizational scale 11: Low to high (depending on nation's developmental state) |
| Hierarchist | Continuous accessibility to resources for sustainable development | ... contribution of a product system to the inaccessibility of mineral resources due to dissipation? | Dissipative flows & Hoarded and abandoned resources* | Dissipation (as well as hoarded and abandoned resources; cf. Dewulf et al., 2021) leads to the inaccessibility of resources, resulting in a lost potential to make use of the economic and use values of resources | 6 | EDP, JRC suggested approach, ADR and LPST | High |
| | | ... potential availability issues for a product system related to mid-term physico-economic scarcity of mineral resources? (Berger et al., 2020) | Supply disruption/ supply risk* | Mid-term supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic and use values of mineral resources | 5 | ADP economic reserves | High |

| | | | | | | | |
|--|--|--|---|--|--------------|---------------------|---|
| | Efficiency of the use of resources with regards to pursuing global welfare through development | ... contribution of a product system to the (economic) externalities of mineral resource use? (Berger et al., 2020) | Extractive flows | Current over-extraction of geological resources leads to lower total economic rent over time, resulting in a lost potential to make use of the economic value of mineral resources | 2 | Future Welfare Loss | Low-medium |
| | | | | Current extraction leads to diminishing ore grades and increasing costs, resulting in a reduced potential to make use of the economic value of mineral resources | 3 | SCP | Low-medium |
| | | | | Insufficient re-investments of economic rent of resources, resulting in a lost potential to make use of the economic value of mineral resources | 4 | LIME2 endpoint | Low-medium |
| | | ... contribution of a product system to externalities (use value and economic value) in relation to mineral resource use, considering hierarchist socio-economic objectives? | Inefficient resource use with regards to hierarchist socio-economic objectives* | Inefficient use of resources and sharing of economic activities along supply chains (e.g. unsustainable supply, non-cooperative distribution of resources and value chains, etc.), resulting in a lost potential to make use of the economic and use values of mineral resources | 8, 9, 10, 11 | N/A | 8: High 9, 11: Medium-high 10: Medium |

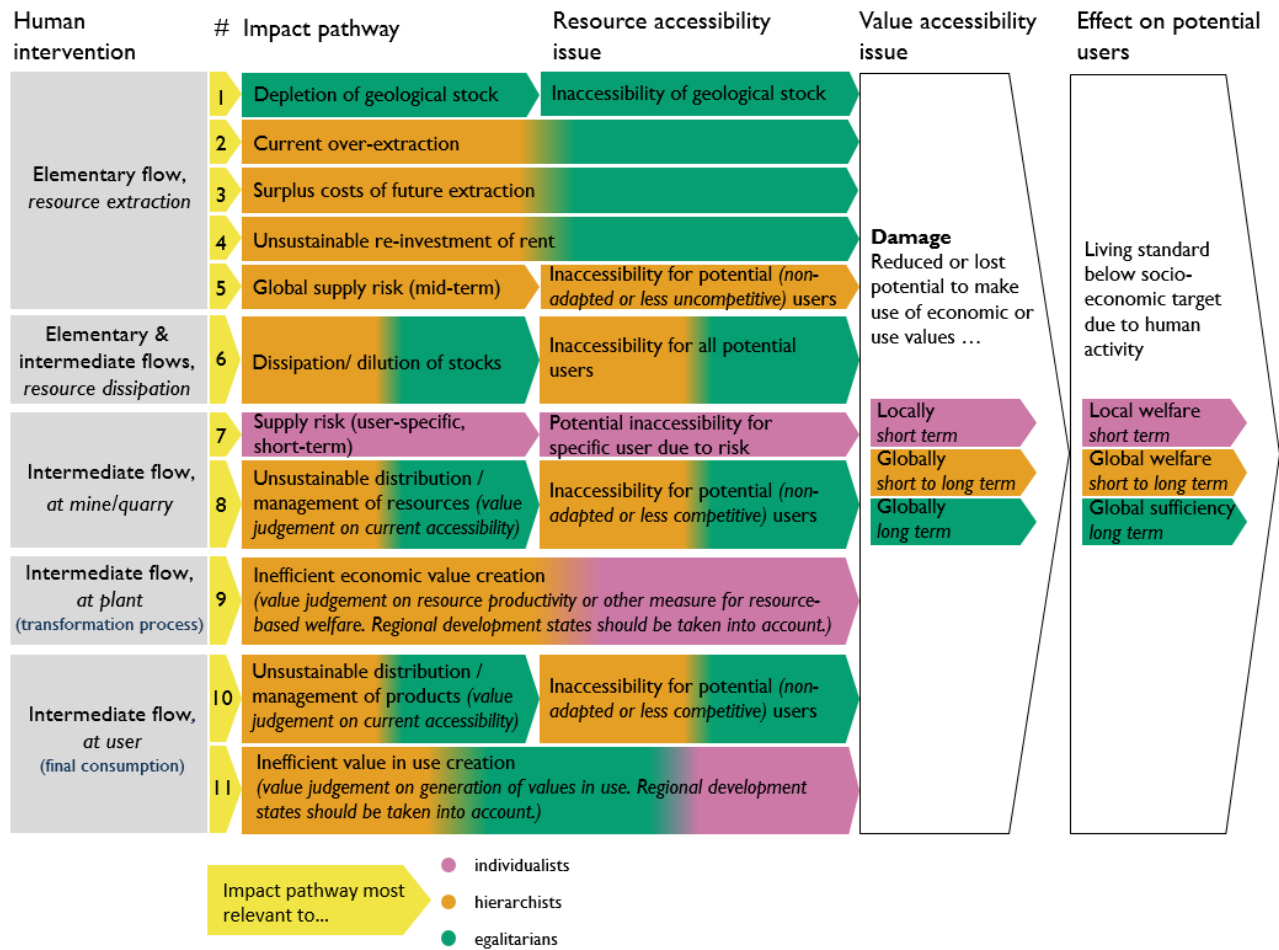


Figure 2-5. Potential impact pathways related to mineral resource use, and the cultural perspectives they are most relevant to. The value accessibility issue is adapted from the definition of damage of Berger et al. (2020).

2.6 Discussion and conclusions

Resources and values are two sides of the same coin and hence cannot be assessed dissociated one from another: managing the accessibility to resources determines which potential users may benefit from their economic value and use value. Depending on one's cultural perspective, different management strategies may be established because they pursue different socio-economic objectives (cf. Table 2-1). Consequently, different aspects related to mineral resource use may be most relevant to each of them (cf. Table 2-2). Our analysis allowed to identify eleven potentially relevant impact pathways, but more may be needed to cover different socio-economic objectives for each perspective. Out of these, seven may be most relevant to egalitarians, three to individualists (which vary based on the geographical scope of their assessment), and nine to hierarchists, as identified in Figure 2-5.

The classification of impact pathways by cultural perspective and their association with existing LCIA methods (Table 2-2) may orientate the selection of LCIA methods to be used by practitioners

depending on their beliefs and on what they value (i.e. which cultural perspective fits them best; cf. sections 2.3 of this chapter and section A.3 of Annex A). The classification helps ensuring a more holistic coverage of the potential impacts related to mineral resource use fitting a specific view of the world. It also proposes a generic hierarchisation of the impact pathways for each perspective in such a way that it may provide some indications for weighting if ever multiple impact pathways are addressed altogether in one same LCIA method to assess the impacts of mineral resource use on the AoP.

We noted that existing LCIA methods may be used to address impact pathways 1 to 7. However, aside the Future Welfare Loss, SCP and LIME2 endpoint methods, LCIA methods considered for this analysis only allow to quantify midpoint impacts. Also, impact pathways 8 to 11 are not addressed by existing methods. Interestingly, they could be thought of as relevant only in the context of social or economic assessment, or in the englobing Life Cycle Sustainability Assessment (LCSA) (Dewulf et al., 2015). Yet, while these pathways may originate from flows that are not addressed within the traditional environmental LCA framework, we have demonstrated that they also relate to the safeguard subject defined by the MR taskforce and hence may deserve consideration. These impact pathways involve value judgements on the current accessibility to resources depending on socio-economic objectives considering regional needs. Indeed, the effects of an inaccessibility to mineral resources for different potential users depends on their specific socio-economic context, and it could be needed to assess these in an analogous way to the regional vulnerability when assessing the impacts of water use linked to the AoP human health (Boulay et al., 2011).

For instance, mineral resources that are used in the upmost optimal way considering specific cultural socio-economic objectives may be considered as having no impact under that same cultural perspective's assessment (impact pathways #8-11). Conversely, resource use may be perceived as impactful under some perspectives when they allow to fulfill *excessive* wants, where *excessive* depends on the perspective. Therefore, socio-economic objectives should be kept in mind if ever LCIA methods are to be developed. Addressing impact pathways #8-11 might therefore involve contribution analyses of supply chains, including processes and products, to the local or global welfare through the economic value and use values they generate. The developments proposed in this chapter reinforce the relation of the AoP natural resources to socio-economic rather than strictly environmental considerations, which is required if resources are to be managed appropriately under a given world view.

Many flows to be characterized are not elementary flows, which was also highlighted as a challenge to overcome for supply risk methods (Berger et al., 2020). Nonetheless, some of the studied LCIA methods already aim to quantify flows in the technosphere (intermediate flows or economic values), while their characterization factors so far apply to extraction flows: it is the case for the ADR, Future

Welfare Loss, LIME2 endpoint, LPST and SCP methods. This trend puts forward the necessity to delve into intermediate flows if it is attempted to assess the damage on the AoP natural resources exhaustively, because it is where the mineral resource-based value (as defined for the AoP natural resources) happens.

We propose that all of the LCIA methods should be linked to an endpoint damage considering economic and use values for specific users, although we acknowledge that quantifying such values may be challenging. Following this proposal, additional developments would be required to assess resource accessibility issues, value accessibility issues, and eventually effects on potential users, as depicted in Figure 2-5. Indeed, it can be noted that existing impact pathways link the effect of water shortages to regionalized aspect of human welfare (i.e., human health) (Boulay et al., 2011). The economic value of resources on markets could be used as a proxy to estimate the lost economic value, as suggested by the JRC to estimate the lost economic value due to dissipated flows (Beylot et al., 2020a). However, market prices are unlikely to represent the actual economic value generated along supply chains, and even less so to represent the use value. Moreover, price may only partly take into account other relevant information such as the scarcity and substitutability of resources (Ecorys, 2012; Henckens et al., 2016). Thus, alternative approaches measuring the value-added of metal flows in specific regions or globally (e.g. based on input-output tables: see Beylot and Villeneuve, 2015 and EXIOBASE3: Tukker et al., 2018) could provide a more exhaustive assessment of the economic value of resources as defined in this paper. At this time, methodological developments are needed to combine dissipation and depletion methods with economic value, use value, and/or substitution evaluations. Finally, a joint assessment of damage including the values obtained from ecosystems would be necessary to take into account the different cultural perspectives holistically.

Methodological choices underlying LCIA methods within a given perspective should be consistent. For example, there has been numerous discussions on the most relevant geological stock to safeguard (Drielsma et al., 2016b; Pradel et al., 2021; Steen, 2006; van Oers and Guinée, 2016), and we here suggest that the stock and LCIA model in question should match with the cultural perspective's view of technological development and its tolerance for risk. For instance, the assessment of depletion under the egalitarian perspective could consider the total amount of accessible resources in the long-term to be better represented by the reserve base or economic reserve of each element, as assessed with the ADP reserve base and ADP economic reserves methods, rather than ultimate reserves. Furthermore, the same reference stocks should be utilized for the assessment of other impact categories (e.g. for depletion and surplus cost) in order to remain consistent amongst the multiple impact pathways under a given perspective.

Additional topics that may deserve further attention for method development were identified throughout our analysis. Characterizations factors could be calculated differently for different mineral resources under different perspectives, depending on the functions they may have for humans in the technosphere. For example, technology metals may be more valuable to hierarchists than to egalitarians. In a similar way, individualists could rely on supply risk (or criticality) assessments that take the current economic importance of resources into account (see e.g. Graedel et al., 2012 and Sonnemann et al., 2015). Moreover, the measurement of dissipative flows may also become part of supply risk assessments (Helbig et al., 2020), since dissipative flows may increase the industry or a nation's dependence on the supply from third parties. For the opposite (yet complementary) reason, recycling was integrated in the GeoPolRisk method (Santillán-Saldivar et al., 2021). Finally, it could be useful to improve the definition of impact pathways with regards to sustainability objectives such as SDGs, as undertaken by the Life Cycle Initiative (2020).

As concluding thoughts, we would remind that LCA is a value-based tool dedicated at supporting design and engineering decisions in the industry, at communicating the environmental profile of products, and at supporting policy-making: it can be expected that professionals or policy-makers in organizations making use of LCA are typically interested in generating resource-based socio-economic value in the short-term, which rather fits the individualist or hierarchist perspectives. Preserving the geological stocks, especially for the long-term, is not much relevant in either's agenda (Drielsma et al., 2016a). Moreover, challenges awaiting humanity in light of on-going environmental changes and the ever-increasing needs of the still growing global population, as articulated in the SDGs, make it more difficult to defend the egalitarian paradigm today than it was a few decades ago. This situation has led to the development of multiple resource indicators that were here associated to different impact pathways and cultural perspectives in order to provide guidance to life cycle assessment practitioners when deciding which LCIA methods may be used altogether to assess the impacts of mineral resource use depending on what they value.

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Chapter 3. Dissipation of mineral resources in life cycle assessment: state of the art and potential ways forward

Building on the conceptual propositions of Chapter 2, we now focus on the consideration of the dissipation of mineral resources in the context of LCA. This chapter is divided in two main sub-sections. The first section presents a state of the art on the consideration of dissipation of mineral resources in LCA. Concepts underlying the dissipation of resources are presented, terminology is defined, and existing approaches are reviewed. Parts of this sub-section are excerpts from the following published book chapter: "Charpentier Poncelet, A., Beylot, A., Muller, S., Villeneuve, J., Loubet, P., Laratte, B., & Sonnemann, G. (2021). Dissipation of minerals in Life Cycle Assessment, in: Pradel, M., Busato, G., Muller, S. (Eds.), *Mineral Resources in Life Cycle Assessment. New Research Developments and Feedbacks from Private and Public Stakeholders*. EcoSD Annual Workshop 2020. Presses des Mines, Paris, pp. 23–35."

The second section presents a conceptual exploration of options allowing to account for the dissipation of mineral resources in LCA. Two options are proposed based on dynamic material flow analysis (MFA) data: (1) to quantify dissipative flows (DFs) by reworking the current life cycle inventories and characterizing the impacts with appropriate LCIA methods accordingly, or (2) to develop characterization factors that integrate dissipation and are applied to current extraction flows. This second section refers to contents from the following published perspective paper: "Charpentier Poncelet, A., Loubet, P., Laratte, B., Muller, S., Villeneuve, J., & Sonnemann, G. (2019). A necessary step forward for proper non-energetic abiotic resource use consideration in life cycle assessment : The functional dissipation approach using dynamic material flow analysis data. *Resour. Conserv. Recycl.* 151, 104449. <https://doi.org/10.1016/j.resconrec.2019.104449>"

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3.1 State of the art

3.1.1 Concepts and definitions

In general, the discussion in the LCA community about the concept of the dissipation of mineral resources relates to a reduced or lost accessibility or functionality of mineral resources due to human activity (Berger et al., 2020; Beylot et al., 2020b; Schulze et al., 2020a; Stewart and Weidema, 2005; Vadenbo et al., 2014). Going forth with the assessment of dissipation has recently been subject to conceptual refinements and methodological developments (Ardente et al., 2019; Beylot et al., 2021, 2020b, 2020a; van Oers et al., 2020). Beylot et al. defined these flows based on an extensive literature review:

"dissipative flows of abiotic resources are flows to sinks or stocks that are not accessible to future users due to different constraints. These constraints prevent humans to make use of the function(s) that the resources could have in the technosphere. The distinction between dissipative and non-dissipative flows of resources may depend on technological and economic factors, which can change over time" (2020b).

DFs thus include resource flows that become inaccessible in the environment or the technosphere (e.g. in landfills, tailings and other material flows) for as long as they are considered to remain inaccessible (Helbig et al., 2020; Zimmermann and Gößling-Reisemann, 2013). As indicated in the definition, there are multiple factors that can affect the flows being considered as dissipative (Ardente et al., 2019; Beylot et al., 2020b):

- A flow that is dissipated must be a resource flow to begin with. To be a resource, the mineral entity should be deemed to have intrinsic value or utility for human beings (when an anthropocentric perspective is adopted), with the potential to provide a function. For example, as argued by Owsianiak et al. (2021, article in press), copper traces in coal (below a certain concentration) may not be considered a resource, whereas copper in ores (over a certain concentration) is.
- The considered time scope may influence which flows are deemed dissipated (i.e. inaccessible) and which are not, since accessibility depends on technological and economic feasibilities. For instance, flows of resources ending in landfills and tailings may be considered dissipated in the short term (e.g. 25 years), but not in the long term (e.g. 500 years) if it is assumed that future economic conditions and technological advances will make them accessible again. As discussed in Chapter 2, assumptions on the future recoverability of resources may depend on one's cultural perspective.

Furthermore, the definition of dissipation, as provided above, relies on keywords such as *resources*, *constraints*, and suggests a temporal scope ("*future users*", "*which can change over time*") which may induce flows that are considered as DFs of resources when assessing the impacts of human activities on the AoP. A careful interpretation of these keywords is central to the concept of dissipation. For instance, identifying the share of mineral entities to be considered as resources is a pre-requirement to distinguish flows that are to be considered as dissipative (Beylot et al., 2021, 2020b). This is a fundamental problem as what is considered a resource may vary between LCI database developers, LCIA method developers and LCA practitioners. The definition of resources and the implications of using one definition or another on what should actually be protected in the AoP should be clarified.

This means that two aspects deserve particular attention: the definition of resources, and the implications of time horizons on the definition of resources. Different definitions of resources are used by different stakeholders, which generally reflect the utility or value that resources have for them. We estimate that the relevant definitions of particular relevance in LCA are those considered by the industry, and that considered by LCA experts (LCI databases developers and LCIA method developers). We hereby present and analyze the definitions of resources amongst extractive industries, life cycle inventory database developers, and that proposed for the AoP natural resources. We then analyze the implications it could have on assessing damage to the resources as defined for the AoP.

3.1.1.1 Different definitions of resources for different stakeholders

In Chapter 2, we presented a definition of resources and of their economic and use values for society under a life cycle perspective. In this section, we explore how different stakeholders may define resources, and how these definitions may interfere with the LCA framework.

3.1.1.1.1 Consideration of mineral resources by extractive industries

The mining industry defines mineral resources as "a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction" (CRIRSCO, 2019). The mineral resources are reclassified as mineral reserves if they are deemed currently economically mineable, including the allowances for losses (CRIRSCO, 2019). Thus, the mineral resources are targeted for extraction only if it is prospected by the industry that the demand for a resource will lead to profitable sale prices: for this, they must be accessible economically with current technologies (Drielsma et al., 2016b), but also accepted socially given the potential environmental externalities of mining projects (Kerr, 2014; Northey et al., 2018). Similarly, economic concerns are the main limiting constraints to recovery for recyclers (Ciacci et al., 2017; Dahmus and Gutowski, 2007), although recycling should not be assumed to always be environmentally beneficial (Reuter et al., 2019; van der Voet et al., 2013).

Through their activities, extractive industries aim to capture an economic value of resources, i.e. the rent of mineral commodities. When the processing costs, including transport, are higher than the anticipated value in exchange (or economic value), minerals are not considered as resources and are not targeted by the extraction processes. The host metals and other elements or minerals contained in the ores which cannot be extracted technically and economically from the ores or from the recycling flows typically end up in different sinks: the environment, other material flows, tailings or landfills (Helbig et al., 2020; Licht et al., 2015; Thiébaud et al., 2018).

3.1.1.1.2 *Consideration of mineral resources in life cycle inventories*

Widespread LCI databases, i.e., the ecoinvent version 3 (Wernet et al., 2016) and Gabi databases (Kupfer et al., 2020), consider resources either to be the content of elements in ores that is targeted by production processes (ecoinvent), either solely the output of these processes (Gabi). They account for inflows of resources to a product system (elementary flows) either directly as metallic elements targeted by the production processes and sold by the mine (e.g. copper and gold), either as the ores containing the targeted elements (copper and gold) in addition to gangue (Berger et al., 2020). In the former case, descriptive of GaBi databases, only the metals targeted by metallurgical processes are accounted for as resources. The resources are directly considered to be the targeted metal content in the ores, or the targeted minerals (e.g. sand, lime, natural stones) (Kupfer et al., 2020). In the latter case, descriptive of ecoinvent databases, the ores are considered to be the resource, and all of the targeted metals contained in the ores are reported in addition to gangue, which represent the part of the extracted rocks and ores which are not targeted by the primary production processes (Classen et al., 2009; Moreno Ruiz et al., 2019; Weidema et al., 2013). The extraction of elements that are disposed of as gangue (valueless rock for extractive industries) is not considered as an elementary flow, and thus may not currently be accounted for with LCIA methods.

This conception of resources based on the fraction of the ores that is of (economic) interest in the short term rather aligns with that of the industry and its stakeholders (e.g., governments, industries purchasing resources, and shareholders). The two LCI databases thus implicitly distinguish between elements or minerals to be considered as resources and non-resources (or gangue) in the short to medium timeframe (i.e., over the lifetime of mineral resources at given mining sites, as per the industry's definition, until it has been depleted).

3.1.1.1.3 *Consideration of mineral resources for the area of protection Natural resources*

The Life Cycle Initiative's taskforce on mineral resources (MR taskforce) recently proposed a consensual definition of mineral resources to be protected in the AoP natural resources: "*Mineral resources are chemical elements (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand), as*

embedded in a natural or anthropogenic stock, that can hold value for humans to be made use of in the technosphere" (Berger et al., 2020). The definition does not precise a timeframe; yet, it could be considered that, under different cultural perspectives (Chapter 2), humans include both current and future generations, i.e., over the long or very long term. Hence, both primary and secondary sources of mineral resources that may be needed to answer human needs and wants of current and future generations could be safeguarded in the AoP.

Figure 3-1 illustrates two different conceptions of mineral resources in the environment (primary resources) and in technosphere (secondary resources), for humans in general (i.e., in line with the definition for the AoP) and for industries (i.e., mostly in line with widespread LCI databases). Non-resources are identified in dark grey.

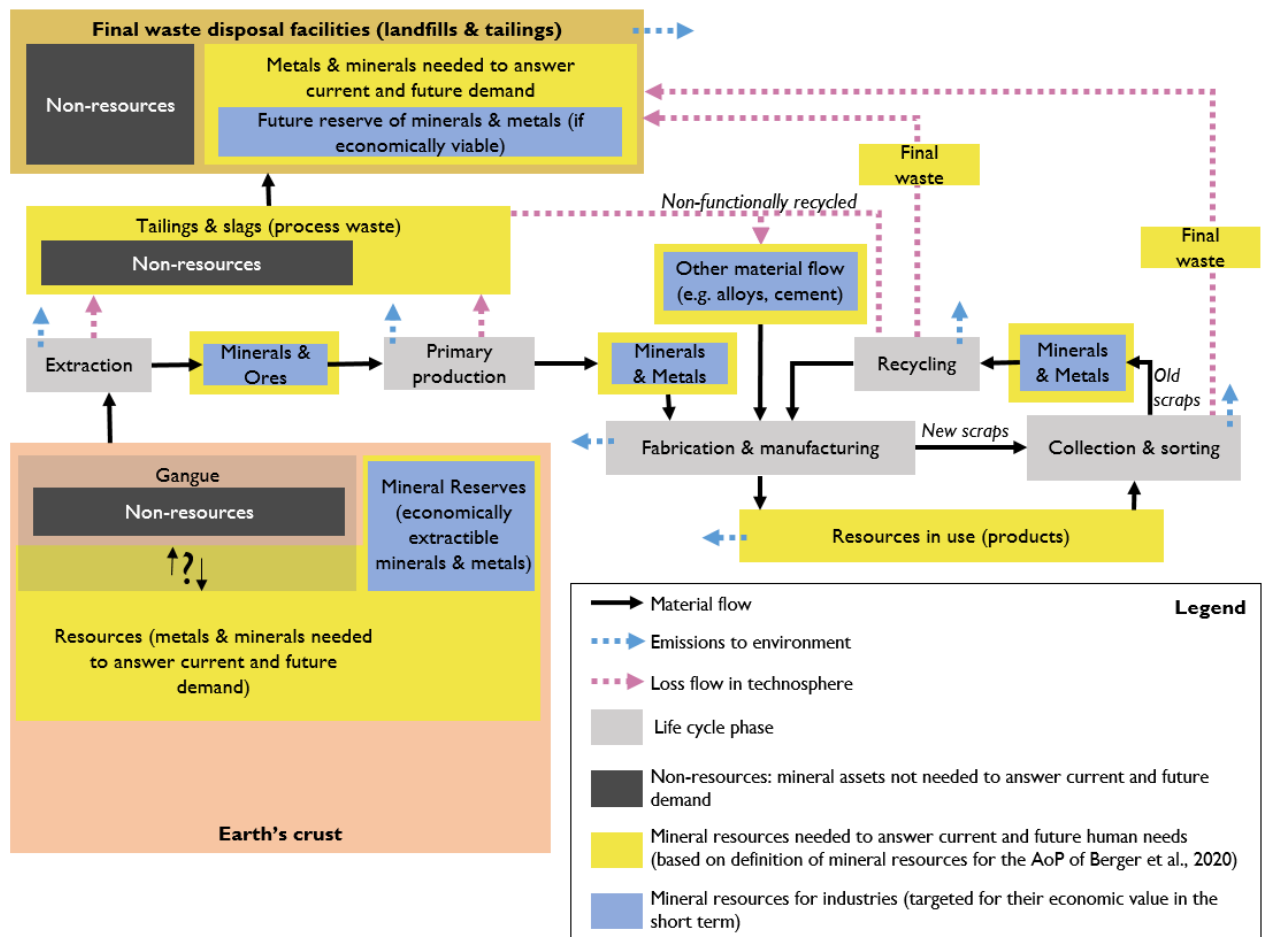


Figure 3-1. Resources as considered by industries (blue) and for humans in general (yellow) as part of geological or anthropogenic stocks along the anthropogenic cycle of minerals. The question mark indicates that there may be an overlap between metals considered as (economically) worthless for extractive industries and resources needed to meet future human needs. These worthless metals, discarded in slags or tailings, may either be mixed in construction materials (e.g., copper slags used in cement), either stockpiled in final waste disposal facilities.

While in the short-term, resources identified as such by the industry may be most relevant in terms of economic value, it is possible that some of the discarded non-resources could in fact be also be considered resources under the definition of the MR taskforce. Indeed, when looking afar in time, the conception of resources augments as the amount of resources that are expected to be needed in the economy to answer the needs and wants of the future generations expands.

3.1.1.2 The effect of time horizons on the definition of resources

As shown in Figure 3-1, the industry's definition of resources is likely to represent a smaller share of mineral flows than the definition for the AoP, because it is mostly reliant on short-term techno-economic feasibility of their use to generate an economic value. Contrastingly, the definition of mineral resources to be protected in the AoP natural resources could include all mineral resources that could be of potential value to humans over a longer time horizon, relevant to hierarchists and egalitarians (cf. Chapter 2). For instance, the share of ores that is not currently economically beneficial to extractive industries today, and hence discarded as waste, could in fact be considered as resources in the future. Under such an understanding, all of the metals and minerals present in the natural and anthropogenic environments that could be deemed useful for current and future generations could be considered as resources, regardless of the current economic and technical feasibility of their production. It should be noted that this latter definition generally goes against current considerations of resources in LCI databases for by extractive industries, as they are mostly aligned on the current economic feasibility of production.

3.1.1.3 On the future accessibility of resources contained in waste

Some of the minerals contained in mining waste (tailings), in primary production waste (slags), or in landfilled end of life products, may be considered as resources in some situations. For example, copper slags are reused on a large scale (Cusano et al., 2017). However, much of the tailings and slags are not directly reused, possibly because the market for such bulk materials can be considered as a local one, as it is the case for natural aggregates (Habert et al., 2010; Ioannidou et al., 2017). In that situation, the resources contained in processing waste are disposed of and made inaccessible at least temporarily, and at worst permanently. Similarly, as materials that voluntarily constitute a product were by definition resources to begin with, it can be considered that obsolete products that are landfilled contain resources that are made inaccessible. Given the pre-mentioned crucial importance of waste collection and recycling for the sustainability of resource management, and the low functional recycling rates for most mineral resources (European Commission, 2011; Graedel et al., 2011), addressing these flows seems particularly important.

Some resources could possibly be extracted from tailings or landfills in the future if proper strategies and technologies are made available (Ayres et al., 2002; Dewulf et al., 2021; Falagán et al., 2017; Sapsford et al., 2017; Winterstetter et al., 2015). Several factors, such as the technological developments and the economic feasibility of re-mining, may determine whether the resources will remain unused in landfills, or if they will be transferred in the economy after a hibernation period. For instance, tailings have already been re-mined for gold in South Africa, for cobalt in Uganda and for neodymium and rare earths in China (Blengini et al., 2019; Stewart and Weidema, 2005; Zhang et al., 2014). For these reasons, it is accepted that the threshold between dissipative and non-dissipative flows may evolve with time as technological and economic factors vary (Berger et al., 2020; Beylot et al., 2020b). Since these factors may evolve over time, the time horizon which is considered may influence whether resources should be considered as dissipated or not (Beylot et al., 2020b). In making such prospective evaluations, the potential limitations to the future recoverability of resources should ideally be evaluated.

Two potential constraints to future recovery were identified in the literature. These considerations should be taken into account when evaluating the future accessibility of these deposits. First, the future mining of waste will not benefit from the same conditions for economic extraction as primary extraction or direct recycling after the end of life. Much like primary extraction from geological stocks, economic and technological constraints will likely influence which waste deposits can be re-mined in the future, and which minerals or elements are targeted for re-mining. As most of the valuable carrier metal has already been extracted from the ores, tailings have higher odds to remain below economic and technical accessibility, making re-mining "much more challenging, expensive or even impossible" compared to the opportunity to extract them during primary production (Graedel, 2018). For instance, even in the case of the Bayan Obo tailings (that is, despite the high concentrations, relatively high economic value of recoverable elements, and the much larger than average size of the tailings deposit), Zhang et al. (2014) mention that it is challenging to re-mine the neodymium and rare earths economically. Put briefly, the investments required for the logistics and the deployment of new mining operations seem likely to be an important limit to the economic feasibility of re-mining small concentrations and/or total volumes of resources. Similar limitations can be expected to be faced for resources stored in landfills, since the current waste management processes mainly target bulk materials and valuable precious metals, while the rest gets landfilled (Graedel, 2018; Løvik et al., 2015; Velis and Brunner, 2013).

Second, in the specific case of tailings, chemical and physical processes enhance the risks of metal emissions to the environment once they are stored in tailings (Guo et al., 2013; Varrica et al., 2014; Wang et al., 2019). These emissions are currently assessed in widespread LCIs based on the modelling

of physicochemical interactions within tailings and the proximate environment (Doka, 2017, 2008; Turner et al., 2019).

3.1.1.4 Implications for the definition of dissipative flows

Following the discussion of the previous sub-section, the future mining of waste disposal facilities should not be expected to be systemically operated from every tailing deposits nor for every mineral resource in the future. It seems plausible that much of the resources stored in tailings or landfills will in fact remain unused for a long period, if not forever (Helbig et al., 2020). Flows of resources that end up in final waste deposits could be considered as recoverable in the future to some extent, but not entirely. Looking at cultural perspectives discussed in Chapter 2, one could expect that the most optimistic on the capacity of humans to adapt would tend to predict great technological advances and a relatively fast recovery of flows of metals ending in waste disposal sites, whereas egalitarians would be the most pessimistic and could anticipate that most if not all metals will not be recovered.

3.1.2 Constraints to the potential to make use of mineral resources

In the following sections, we investigate the constraints to the accessibility of mineral resources and the way these constraints may evolve over time. In order to clarify which resource flows may be considered as dissipative (following the definition of DFs presented in section 3.1.1), we here investigate which human-related factors may impede the accessibility of resources, and how environmental, social, technical and economic factors may come into play in the future. These factors are here termed *constraints*. We here acknowledge the recent works of Dewulf et al. (2021), in which actions that compromise the accessibility of metal resources were identified: emissions to the environment, landfilling, tailing, downcycling, hoarding and abandoning. Building on these, we identify constraints that may prevent humans from making use of metal resources. Figure 3-2 presents the overview of stocks, flows, and sinks for mineral resources. The different constraints leading to a change in the potential to make use of the value of resources are identified with numbers 1 to 8, and are detailed throughout subsections 3.1.2.1 to 3.1.2.5. As defined earlier, the flows that are made inaccessible due to human activities (i.e., after their extraction from geological reserves) may in some cases be dissipative. Constraints to the accessibility of geological reserves are also identified on the figure.

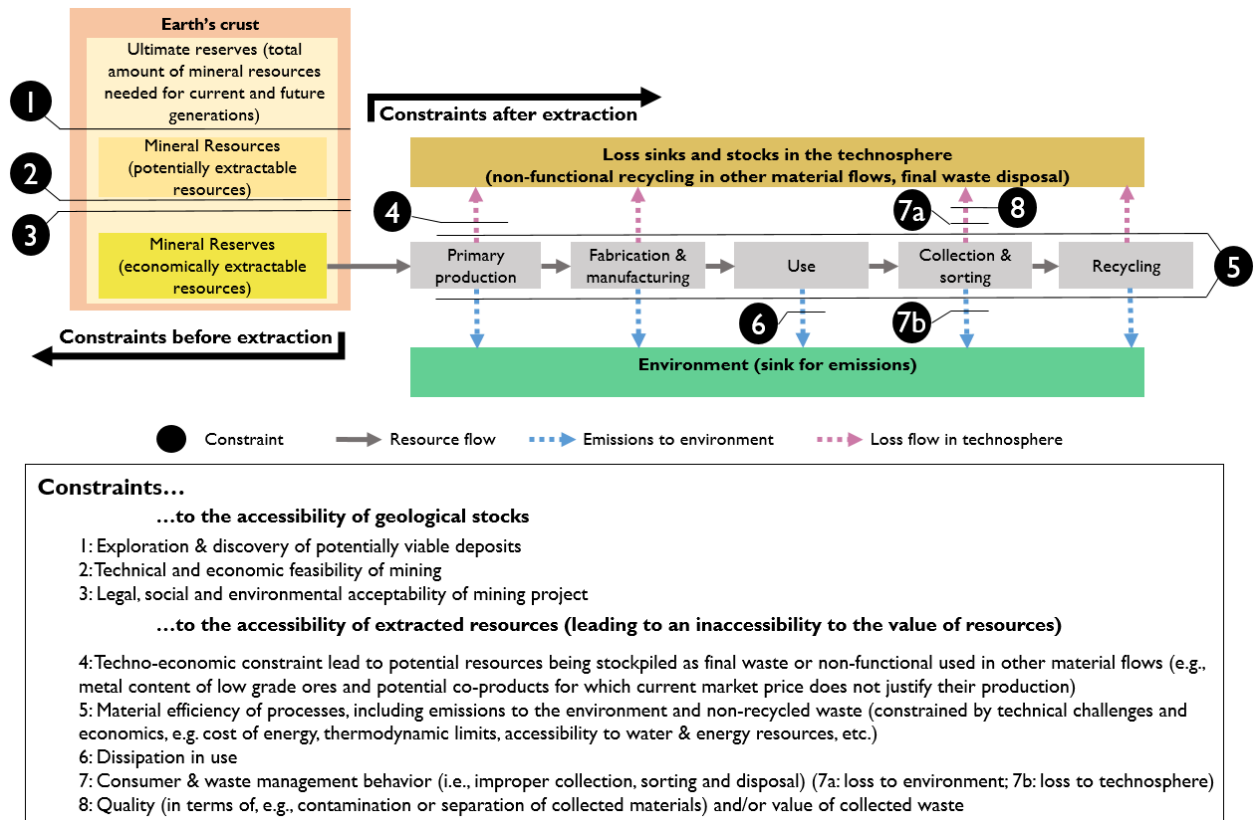


Figure 3-2. Cradle-to-grave stocks, flows, and sinks of resources across their global value chain, and constraints to the potential to make use of them before and after extraction. Constraints to make use of the value of mineral resources are identified with numbers 1 to 8. The primary production phase is considered to transfer minerals from the environment to the technosphere. Constraints 4 to 8 may lead to dissipative flows (emissions to environment or loss flows in the technosphere) for as long as these flows are inaccessible due to different constraints.

3.1.2.1 Constraints to the accessibility of geological resources

Several constraints may determine whether mineral resources become accessible from geological stocks or not. First, they must be discovered: this depends on the anticipated need to search for new deposits (constraint #1) (Ali et al., 2017). When they are known to exist, resources remain inaccessible in the geological compartment until they become economically and technically extractable for the industry, given the state of market demand, politics, markets and technology (Drielsma et al., 2016a; Schulze et al., 2020a). Thus, the economic viability of projects may be seen as one constraint to access resources (constraint #2). Aside from current and anticipated demand in the short term, it can be moderated by multiple factors, e.g., by policies, taxes, subsidies, investment in technology development. Additional external factors may impede the growth of the extractable reserves, now or in the future, such as an adverse social perception of mining activities and of its environmental externalities, the global impacts of the extractive industries and of resource use, more restrictive regulation, and the competition with other production systems for input resources such as land, energy

and water (Ali et al., 2017; Graedel et al., 2012; IM4DC, 2014; Lèbre et al., 2019; Northey et al., 2017; Wall et al., 2017). Finally, the in-situ functions of minerals that contribute to ecosystem services may prove to be a limit to their accessibility. These various environmental, social and legislative factors are grouped under constraint #3.

Once ores have been mined from the ground, the current demand and market price for some potential content in metal resources may be too low to justify their production. As mentioned in section 3.1.1.1.3, these typically end up mixed in other material flows or stored in final waste disposal facilities (constraint #4). They may also be used for the recultivation of mining sites, as it is often the case in aluminium mines (Classen et al., 2009).

3.1.2.2 Constraints for primary production

Mineral resources are present in different environmental compartments from which they may be extracted by human processes in order to use them in the technosphere. We hereby qualify as *desirable* the mineral resources that are targeted by the extraction processes. The rest of the metallic elements, minerals or aggregates contained in ores and consequently in process wastes are qualified as *undesirable*.

At the primary production step, the overburden is first removed to access the desirable minerals or the ores containing them. Then, ores are separated from the undesirable gangue. Desirable mineral resources can be either used directly as found in the environment (e.g. sand, clay), either broken down into smaller fractions to obtain higher concentrations of specific elements (e.g. copper) or configurations of elements (e.g. gypsum). This latter step is called beneficiation.

The amount of raw materials needed to obtain a certain quantity of desirable mineral resources depend on the material efficiency of extraction processes and on the ore grade (concentration of desirable resources) of the deposit (constraint #1). When the desirable resources are elements, these are beneficiated from the ores through successive various metallurgical processes (e.g. smelting and refining). At this stage, the different process wastes (slags) are either reused in various low value applications, either disposed of in landfills as final waste. The supplies of carrier metals from mineral reserves are meant to answer current demand (Elshkaki et al., 2018; Meinert et al., 2016).

The production of potential by-products much depends on the amounts extractible from the ores of other metals and the current market for these resources (Frenzel et al., 2017, 2015; Løvik et al., 2015). Since carrier metals are the main economic driver for extraction (Graedel, 2018), potential by-products often end up in slags because of techno-economic constraints (constraint #4). The yield of production

processes for these by-products may follow any course in between these two extremes, which are driven by their prospected economic value given current demand and processing costs:

- Co-elements are overabundant in ores in comparison to demand. Few or no efforts will be made to separate them: they are undesirable elements that will mostly end up as impurities in the carrier metal flow or be dispatched in slags during primary production.
- Co-elements are insufficient to answer demand. Maximum efforts (within economic and technological constraints) will be made to separate them; small amounts will end up as impurities in the carrier metal flow or be disposed of in slags during primary production.

As noted earlier, discarding undesirable metals does not mean de facto that they should not be considered as a resource to be safeguarded in the AoP. It can only be assumed that they are not required to answer the current demand for supply chains and end-market products. In some situations, the situation could evolve in such a way that the discarded metals are needed in the (future) economy, for example if mining for the host metal slow down, if new functionalities are found for the currently undesirable elements or if the demand grows more rapidly for it than for its host metal. For instance, many processes have been developed to re-mine tailings at the Bayan Obo mine in northern China, in which large amounts of rare earths and neodymium had been stockpiled (Zhang et al., 2014). In this situation, the initially undesirable elements were discarded, and were later considered as a desirable resource by the industry once they became economically extractible with the rising market demand.

3.1.2.3 General processing constraints

After primary production, mineral resources undergo various processing steps to bring them in the form that has a function for humans in a final product. The products are used until they become obsolete, after which they may be collected and either recycled into new products, either disposed of in landfills. Metals can theoretically be recycled indefinitely within the thermodynamic limits since they are indestructible (Kennedy, 1994; Young et al., 2001), except in the marginal cases of radioactive transformations and dissipative losses in space (Schulze et al., 2020a; Tilton et al., 2018). Still, there are inevitable losses at every life cycle stages due to the inherent limits of processes (Cullen, 2017; Graedel, 2018; Reuter et al., 2019). For example, the imperfect physical separation of particles and components at the sorting phase is another limit to their subsequent recycling (Grimaud et al., 2018; Nakajima et al., 2010; Reuter et al., 2019). Subsequently, some processing constraints may arise during the recycling of mineral resources. For instance, some metals remelted from steel alloys may become tramp elements in other material flows, end up as slags waste, or get non-functionally recycled in other material flows (UNEP, 2011). Similarly, configurations of elements, used mainly in construction materials such as cement, can only get downcycled into different uses in which the initial properties

of the minerals are not specifically exploited, because these minerals can't be separated and brought back to their initial particle form (European Commission, 2011). The different techno-economic constraints for each main life cycle phase aside from the use phase are grouped under constraint #5.

3.1.2.4 Dissipation in use

DFs may occur due to the way resources are used in products (e.g., zinc or titanium dioxide powder used in creams), or because products are voluntarily dispersed in the environment to obtain a function (e.g., copper used in pesticides) (Ciacci et al., 2015; Dewulf et al., 2021). Other typical losses to the environment include the corrosion of steel exposed to the outdoor environment, the abrasion of car tires, etc. The dissipation in use of mineral resources are a constraint to the future accessibility of these resources (constraint #6). Ciacci et al. called these "losses by design", as the design of products imply their eventual dispersion in the environment. Therefore, it should be noted that this constraint could in fact be attributed to the product conception stage rather than to the consequent dissipation in use.

3.1.2.5 Constraints to waste management

Collection and sorting is a crucial step to later improve the recycling of materials: together, these steps are at the heart of sustainable resource management (Downing et al., 2020; Reck and Graedel, 2012). Multiple constraints affect the recyclability of resources from the end of life phase to its functional recycling. A first cluster of constraints is management behavior, as consumers and waste managers can improperly sort, handle and dispose of the wastes (constraint #7a and b). These include the hoarding of obsolete products (Dewulf et al., 2021; van Oers et al., 2020) and the improper sorting of waste by consumers, grouped under constraint #7a, as well as products that are abandoned or lost in the environment (constraint #7b). Although it is of non-mineral origins, the accumulation of plastics from e.g. plastic bottles and fish nets in terrestrial and marine ecosystems is probably the best example of such a cause of resource mismanagement and of its impacts (Geyer et al., 2017).

Another constraint to the recycling of minerals is the quality and the value of the waste flow, which may impede the recovery of metals and their recycling in high quality flows (constraint #8). The flows of old scraps of metal must be of sufficient quality if they are to be recycled into pure elements or high quality alloys (Ciacci et al., 2017; UNEP, 2013). Similarly, high volumes of highly dispersed scarce elements in the electronic waste flows may impede their collection and recovery (Ari, 2016; Horta Arduin et al., 2019). An imperfect separation of the different materials can lead to non-functional recycling or to the landfilling of resources. Non-functional recycling leads to the decreasing quality of material flows, which may affect the function that can be obtained from them.

These constraints are intertwined with the regional infrastructure, waste management and recycling practices, which are other factors influencing waste management behavior. For example, if no

recycling facilities are implemented on a territory, the waste management strategy might consist in landfilling all of the waste. The latter factor may vary importantly between countries, especially for those of different development states (UNEP, 2011). In sum, the effective recycling of end of life products depends on the regional infrastructure and management practices, on their technical recyclability (locally or abroad), on the economic value of the waste flows (given the costs of transport and processing).

3.1.3 Current developments of dissipation-oriented methods

Besides the work developed in the context of this thesis, two working groups have followed up on the recommendations of the EC-JRC and of the Life Cycle Initiative, and have published methods to assess the impacts of dissipation of mineral resources in LCA. The first are the follow-up works of the EC-JRC (Beylot et al., 2021), in which a method has been proposed to identify DFs at the unit process level. It is further suggested that price-based CFs can be used to assess the impacts of these DFs. The second are outcomes of the EIT Raw Materials' SUPRIM project, led by Leiden University's Institute of Environmental Sciences (CML), Ghent University's Department of Green Chemistry and Technology, and Euromines (Schulze et al., 2020b, 2020a; SUPRIM, 2019; van Oers et al., 2020). As an output of this project, an LCIA method, called the Environmental Dissipation Potential (EDP), has been proposed (van Oers et al., 2020). Its CFs are applicable to emission flows in existing life cycle databases. Another ongoing project called the Abiotic Resource Project has been launched by the International Council on Mining and Metals (ICMM) (Euromines, 2020). There is no publicly-disclosed information yet, although a scientific paper is on-going revision process (Owsianiak et al., 2021). The advances and general aspects of the two publicly disclosed approaches are described below.

3.1.3.1 Joint Research Centre's suggested approach

The rationale behind the EC-JRC approach is to report DFs of mineral resources at the level of unit processes, in mass units (Beylot et al., 2020a). This reporting is performed considering a predefined list of DFs of mineral resources to a number of compartments (e.g. dissipative flow of copper to the environment). Beylot et al. (2021, 2020a) suggest taking a short-term perspective (25 years), so that any flow of resources to i) environment, ii) final waste disposal facilities and iii) products in use in the technosphere (with low-functional recovery) are reported as dissipative.

This approach first requires carrying out substance flow analyses at the unit process level, before identifying the DFs of resources and reporting them in the inventory. It is suggested that this approach at the inventory level be combined with a price-based impact assessment model to characterize the impact induced by mineral and metal resource dissipation. It has been applied to a case study relative to primary production of copper, using ecoinvent datasets as a basis to exemplify the potential of

replication to a larger number of datasets in standard LCI databases. However, at this stage the approach still requires further development before it can be routinely implemented.

3.1.3.2 Environmental dissipation potential (EDP) method

The SUPRIM work group has worked on framing the issue with mineral resource use through a consensus-finding process (Schulze et al., 2020a) and developed a method evaluating the impacts of the emissions of mineral resources to the environment on the AoP Natural Resources, called environmental dissipation potential (EDP) (van Oers et al., 2020). Conceptual developments and equations for short term (25 years) methods are provided, including resource hibernation and occupation as additional impact pathways, though no characterization factors for the short term are provided at this time (van Oers et al., 2020). For the long-term perspective (>100 years), it is assumed that all of the current primary extraction is equal to long-term dissipation in the environment (i.e. all that is extracted now will be dissipated in the long term over successive applications). The CFs for the EDP method are meant to be applied to the emission flows in the LCI. Thus, the EDP method characterizes the impacts of the emissions of mineral elements to the environment on the AoP Natural Resources given their respective environmental dissipation potentials.

Different methodological choices have been made in the different approaches. The EC-JRC approach considers the intra-technosphere as well as environmental dissipation in the short term, and only the dissipation (emissions to the environment) in the long term (Beylot et al., 2020a). The SUPRIM approach considers three potentially relevant impact categories (hibernation, occupation and environmental dissipation) which might be relevant for the short term, but only assumes environmental dissipation to be relevant in the long term as part of the EDP method (van Oers et al., 2020). This assumption for the long term is made in the EDP method, and also in the EC-JRC approach as an "hypothetical and simplified scenario" as a complement to the short-term approach (Beylot et al., 2020a). It is justified by the expected economic and technology developments making all of the mineral resources disposed of in tailings and landfills accessible in the long term. Such an assumption seems more probable for some high value and decently concentrated metals; however, it is not certain to which extent this assumption may hold true for all metals. An overview of published existing methods and characteristics is presented in Table 3-1.

3.1.3.3 Discussion on existing methods

Table 3-1. Overview of two acknowledged methods addressing the dissipation of minerals in life cycle assessment

| Approach | Model / Maturity | Resources considered as inaccessible (dissipated) |
|-----------------------------|---|---|
| EDP short term (< 25 years) | Equations available / characterization factors not provided (van Oers et al., 2020) | <ul style="list-style-type: none"> • Hibernation within technosphere (landfill, etc.) • Occupation • Emissions of resources to the environment |
| EDP long term (>100 years) | Characterization factors available (van Oers et al., 2020) | <ul style="list-style-type: none"> • Emissions to the environment |
| JRC short term (25 years) | Modification of life cycle inventories / technical report from the JRC (Beylot et al., 2020a) and scientific publication (Beylot et al., 2021) | <ul style="list-style-type: none"> • Emissions of resources to the environment • Resources in final waste disposal facilities (e.g. in landfills) • Resources in products-in-use, in case of low-functional recovery |
| JRC long term (>100 years) | Modification of life cycle inventories – sensitivity analysis / technical report from the JRC (Beylot et al., 2020a) and scientific publication (Beylot et al., 2021) | <ul style="list-style-type: none"> • Emissions of resources to the environment |

The EC-JRC approach provides relatively detailed information on the DFs occurring at the unit process level, all along the life cycle of the products and systems under study, though the modification of inventories in current major LCI databases appears to be a key complex challenge (Beylot et al., 2020a). The long-term SUPRIM approach, i.e. the EDP method, assumes that the long-term dissipation consists only in emissions into the environment, and considers any emission into the environment as a dissipative loss of resources, although the emissions may originate from non-resource origins. By non-resource origins, we mean that some elements that are emitted come from sources in which they are not considered a resource to begin with, e.g. because their concentration in the medium is very low (Owsianiak et al., 2021). For example, copper traces in coal might end up as copper emissions during coal combustion, albeit not being a resource to begin with. For this reason, Owsianiak et al. (2021) propose a criterion based on a reference concentration (i.e., the average concentration in the upper continental crust) to distinguish between resources and non-resources, so that emissions coming from different sources can be classified as emissions of resources or of non-resources. Moreover, in the EDP method, the emissions from the inventories are contradictorily part of both the cumulative emissions and part of the so-called ultimate reserves, which is proxy-measured from the crustal content (the latter does not get smaller through cumulative extraction in the current version of the method).

3.1.3.4 *On-going testing of dissipation-oriented approaches*

There is an outgoing will to switch from depletion-based to dissipation-based methods for the assessment of the impacts of mineral resource use in LCA. Currently, the Technical Advisory Board of the EC is putting existing methods to test with an application study, with the objective of updating the recommendation for an LCIA method in the context of the Product Environmental Footprint (PEF). Similarly, the ICMM is currently doing an application study using newly developed methods to evaluate how they can be expected to influence the results of impact assessments for different metals.

3.2 Other potential way forward: using dynamic MFA data to account for the dissipation of mineral resources in LCA³

The methods discussed in section 3.1.3 propose interesting options to account for the dissipation of mineral resources in LCA. However, they each present some limitations in terms of current applicability. Indeed, the EDP method so far only accounts for dissipative flows to the environment, whereas an important share of dissipative flows are expected to be lost within the technosphere (Zampori and Sala, 2017). Furthermore, the JRC suggested approach requires important offline manipulations of the LCI, which may well represent an important challenge for its application in LCA studies (Beylot et al., 2020b). Thus, in this this section, we propose other potential ways forward to implement dissipation in LCA based on dynamic MFA results.

As dynamic material flow analysis (dynamic MFA) allows monitoring flows within a system and its outflows within a dynamic timeframe, it enables the calculation of dissipation curves inside different compartments over time for a material or substance. Hence, we propose two options allowing the transition towards the application in LCA of a functional dissipation approach based on dynamic MFA and a specific conceptual LCIA framework:

- The implementation of dynamic MFA dissipation ratios in LCIs to include dissipation into the ecosphere and/ or temporary stocking inside the technosphere and the conversion of these flows in an environmental impact on the AoPs Natural Resources, Human Health and Natural Environment with proper CFs in the LCIA phase (option 1);

³As mentioned in the introduction of this chapter, this section refers to contents from the following published perspective paper: "Charpentier Poncelet, A., Loubet, P., Laratte, B., Muller, S., Villeneuve, J., & Sonnemann, G. (2019). A necessary step forward for proper non-energetic abiotic resource use consideration in life cycle assessment : The functional dissipation approach using dynamic material flow analysis data. *Resour. Conserv. Recycl.* 151, 104449. <https://doi.org/10.1016/j.resconrec.2019.104449>"

- The integration of such mechanisms directly into CFs related to the AoP of Natural Resources based on more generic resource-based dissipation curves for product systems aggregated by product type, industrial sector or at a geographic level such as global or regional (option 2).

In both options, flows for one abiotic resource are represented in a simplified theoretical product system. Input flows to the product system include both primary elementary flows (A) and secondary (B) resources. Intermediate resource flows within the product system are marked as C1, C2 and C3. In option 1, output flows from the product system are distinguished in three different fractions: dissipated to other material flows and final waste disposal facilities (D), dissipated to environment (E), and looped into other product systems (F). D1 to D4 flows are not elementary flows, as they do not cross the technosphere-environment boundary, but still reside in technosphere as unavailable resources, thus impacting the AoP Natural Resources.

Option 1 allows for mass balance check for every process separately and for the system (similarly to the JRC suggested approach discussed above), as well as to link new inventories to dissipation to other impact categories. Option 2 implies a loss of information about where resources are lost over the life cycle, and it would not enable to compare between different systems using a same resource in different ways if a global scale is chosen. However, option 2 can be seen as a prevention indicator for abiotic resource use since it anticipates potential quality losses and DFs over a resource's lifetime that at one moment are not available anymore for recycling and that might lead to environmental impacts within a defined period. The two options, depicted in Figure 3-3, are not mutually exclusive: they could be combined and complemented with other data in order to optimize among the precision of the characterization, data availability, and the feasibility of implementation of the proposed functional dissipation approach in LCA. Indeed, different product-specific phases of the life cycle present product system-dependent dissipation patterns. These could be complemented with external data from resource sub-system studies such as the regionally-linked dynamic MFAs study for different aluminium products completed by Bertram et al. (2017).

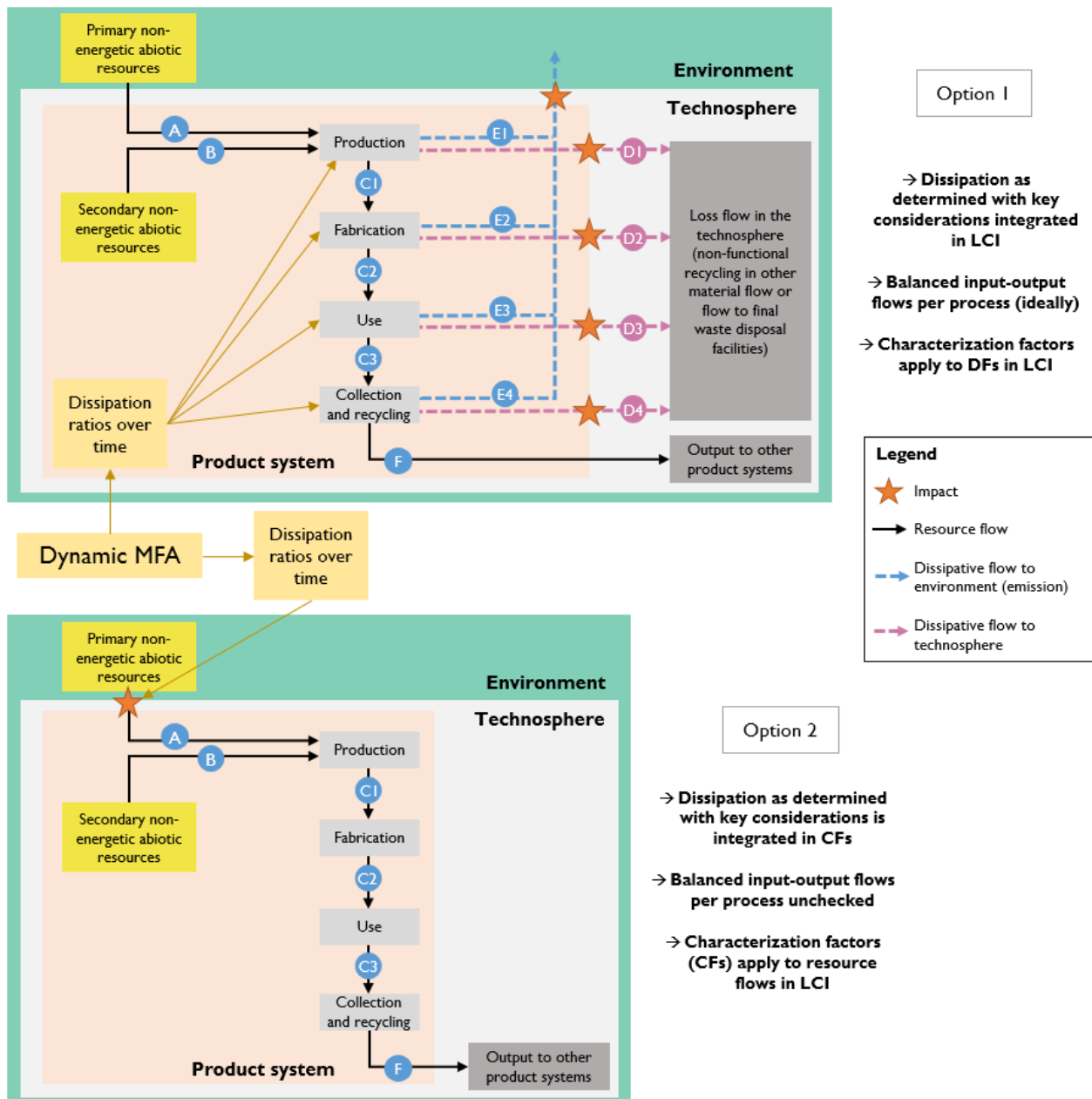


Figure 3-3. Two options for the modelling of dissipative flows in LCA based on a simplified resource-centric viewpoint using dynamic MFA. Option 1 uses dynamic MFA to update or create new LCIs and to compute CFs for the AoPs Human Health and Natural Environment by established methods. Option 2 relies on dynamic MFA to develop new CFs for the AoP Natural Resources.

In the remainder of this thesis, we build on option 2 described above. The proposed approach accounts only for the impacts of the use of abiotic resources, which potentially hampers the functionality for human beings of current and future generations and limits its recycling potential. Moreover, it provides more detailed information about where resources are lost, in particular to the ecosphere over the whole life cycle (Zampori and Sala, 2017), which allows to better anticipate potential environmental impacts. All these aspects offer important arguments to apply the functional dissipation approach and

might facilitate its uptake, once implemented, in characterizing the impacts of non-energetic abiotic resource use in complement to other impact pathways.

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Chapter 4. Lifetimes and losses of metals in the economy

In the second section of Chapter 3, it was identified that dynamic material flow analysis (MFA) data could be used to develop characterization factors (CFs) to assess the impacts of the dissipation of mineral resources on the AoP Natural resources. In this chapter, we develop a dynamic MFA model, collect the required data, and simulate the evolution of sixty-one metals in the economy from extraction until they have been completely lost. We also estimate the lifetimes and losses of these metals to different stocks and sinks.

While most metals are crucial to modern societies, consumption keeps rising following the ever-increasing population, affluence and technology. The quest for resource efficient and circular economies requires improving the retention of metals in the economy. We studied the evolution of a yearly cohort of extracted metals over time and identified where losses are expected to occur in their life cycles. On average, ferrous metals were found to have the highest lifetimes, followed by precious, non-ferrous and specialty metals. Comparing our results with UN Environmental Programme (UNEP)'s recycling statistics shows that taking a life cycle perspective on losses of metals is essential to establish holistic circular economy strategies. Still, we found that losses to waste management and recycling are most important for 43 out of 61 studied metals, suggesting that most efforts remain dedicated to improving designs allowing for sorting and recycling, in combination to ameliorating waste management practices.

Please note that, in this chapter, we use the terminology of "losses" of metals rather than "dissipative flows", since the latter may need to be more strictly defined within the LCA research field (cf. Chapter 3). This chapter refers to the following submitted paper: "Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G. (2021). Lifetimes and losses of metals in the economy. Submitted to Nature Sustainability."

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4.1 Introduction

Vast amounts of metals are needed for our modern societies to thrive and to pursue Sustainable Development Goals (Graedel et al., 2013; UNEP, 2019). Nevertheless, like biological resources (Wackernagel et al., 2021), metal stocks are under the pressure of an ever-rising demand (Ali et al., 2017; Graedel et al., 2013). Consequently, many nations have started to identify commodities for which supply risks pose a particular threat to their economies. The European Union and the United States consider about 30 metals and minerals as so-called "critical raw materials", a crucial prioritization approach to secure regional supply strategies (Helbig et al., 2021; Schrijvers et al., 2020).

Circular economy strategies can be proposed as a response to this increasing stress. Minimizing metal losses along supply chains and increasing the lifespans of products help prolonging the lifetimes of metals in the economy, and increasing the value they generate for humans while reducing possible environmental impacts and mitigating potential supply risks for future generations (Moraga et al., 2021; Reuter et al., 2019). These strategies may also help reducing greenhouse gas emissions from the metal production sector (Ciacci et al., 2016; Reuter et al., 2019; Watari et al., 2020), responsible for 7.9% of the global emissions (Lamb et al., 2021).

Losses of metals may be considered the negation of circularity since they become inaccessible for future use (Beylot et al., 2020). Material flow analyses allow tracking losses of metals with a life cycle perspective. The fate of metals can be dynamically evaluated over time by considering the lifetime of products put on the market and identifying where these losses occur. However, for many metals, there is no comprehensive global material flow analysis available so far (Graedel, 2019). In this context, we seek to improve the knowledge based on the contemporary losses of metals. Relying on a wide-ranging data collection stage and the MaTrace dissipation model (Nakamura et al., 2014), we evaluate the lifetimes of 61 metals in the economy and attribute cumulative losses to different life cycle phases over time. Our results are compared with the UN Environmental Programme (UNEP)'s global recycling indicators available for multiple commodities (UNEP, 2011), revealing the importance of taking a life cycle perspective when setting up circular economy strategies, or more generally, aiming for a more sustainable management of metals.

4.2 Methods

4.2.1 Global cycle of metals

We study the global trends of metal flows and use stocks over their life cycle (Figure 4-1). The lifetimes of metals represent the average duration of their use in the economy, from mining until they have been entirely lost to final waste deposits or the environment. We define losses as flows of metals

emitted to the environment, stored in waste disposal facilities, or diluted in a material flow where its specific characteristics are no longer made use of (Helbig et al., 2020). Loss rates are calculated as the inverse function of the lifetime and represent the rate at which extracted metals become unavailable for further use due to human activity.

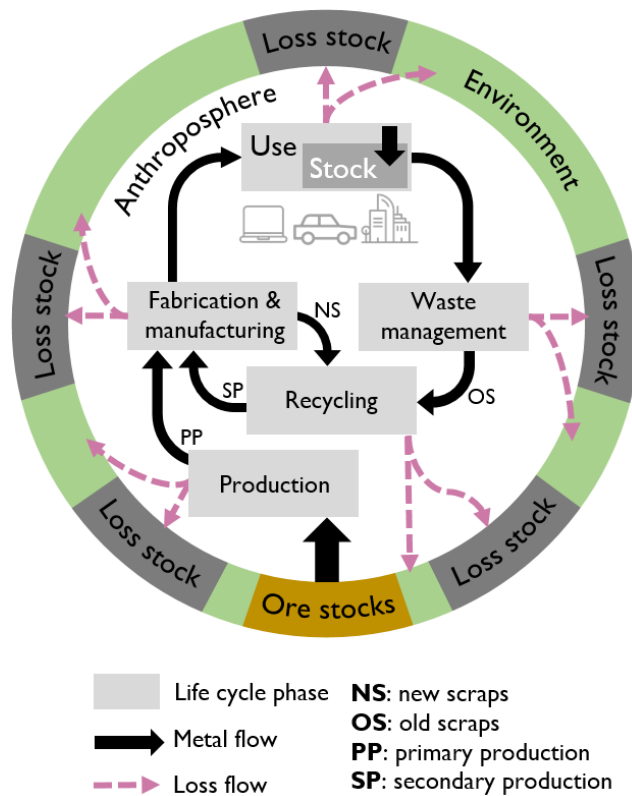


Figure 4-1. Global cycle of metals (adapted from Chen and Graedel, 2012). Loss flows are either emissions to the environment, non-functionally recycled metals ending up in other material flows, or losses to final waste disposal facilities (landfills, slags and tailings storage facilities).

The evolution of metal losses over time is derived from the contemporary yields of processes amongst the main life cycle phases and the distribution of metal applications per end-use sector and their corresponding lifetimes; they are not a forecast (Helbig et al., 2020). The year-by-year in-use stocks for each metal detailed per sector and losses per process over the next 1 000 years are provided in the Supplementary Data provided online⁴. Moreover, we provide a detailed and updatable dataset,

Please note that the following dataset and code will be updated and published online along with the article entitled “Lifetime and losses of metals in the economy” by Charpentier Poncelet et al. (2022). This article and its supplementary content should be accessed in order to ensure getting the up-to-date dataset and code. A temporary version can be accessed with the following links (one link is provided at the bottom of the next page):

⁴ https://osf.io/vdfx3/?view_only=fe51e934544b4514b9fccce34e5a9c1a

including every data point and underlying references that may be a starting point for other studies. The dataset is provided as separate machine-readable files in the standardized ODYM data model for dynamic MFA (Pauliuk and Heeren, 2019), also available online⁵.

4.2.2 MaTrace model

The MaTrace model (Nakamura et al., 2014) allows for tracking losses of resources of an initial cohort of material along its anthropogenic cycle (Godoy León et al., 2020; Helbig et al., 2020; Jarrín Jácome et al., 2021; Nakamura et al., 2017, 2014; Pauliuk et al., 2017). The model is extended to include the yield of the primary production process and runs using global average yields for each of the main life cycle phases (Helbig et al., 2020). It here simulates the fate of one kilogram of metal extracted from the ground over 1 000 years, with a global scope. There is no regionalization of stocks and flows. The conceptual model is depicted in Figure 4-2.

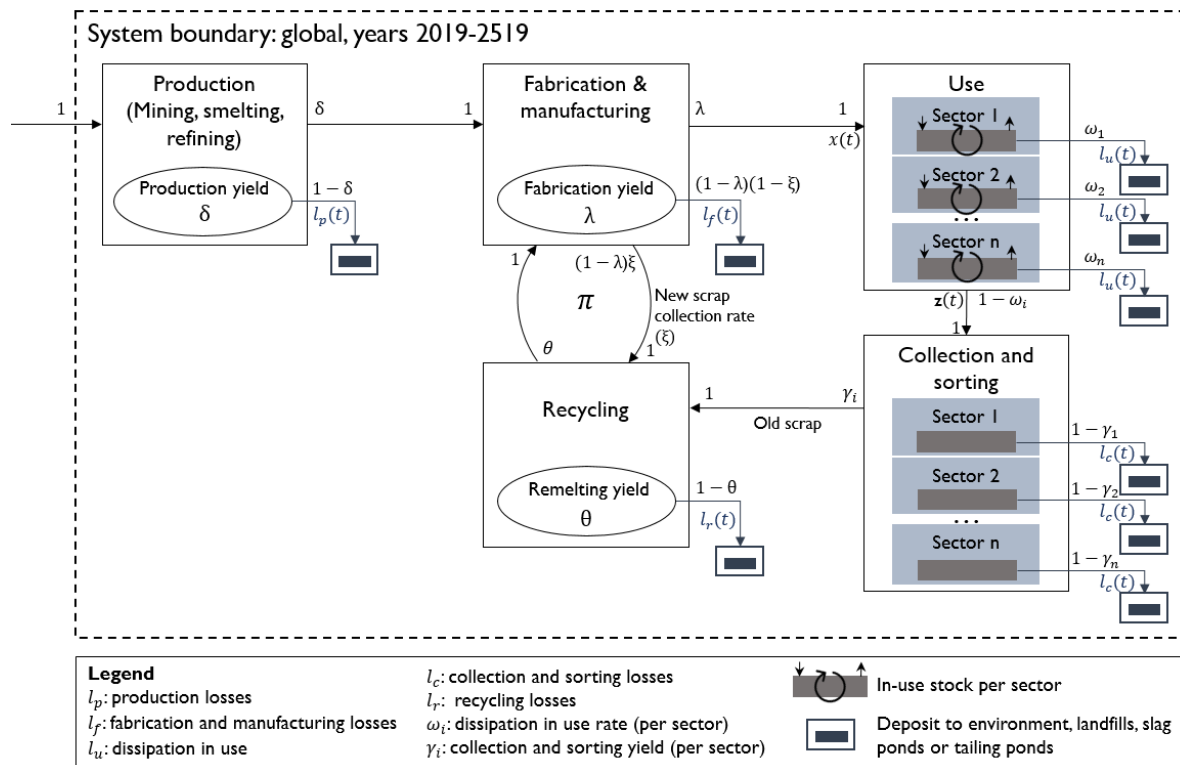


Figure 4-2. System definition and conceptual model (adapted from Helbig et al., 2020)

In order to avoid redundancy with the previous works of Helbig et al. (2020), we refer readers to their article for details on the calculations, as well as to Annex B. The main difference in this model compared to that of Helbig et al. is that losses in the use phase and collection yields are here defined for each

⁵ https://osf.io/87bsk/?view_only=e8b477aa89c1422c861bd9a7ff05e07b

sector and metal, rather than per metal only. The initial cohort of extracted metal is allocated to end-use sectors with the factor α , where the sum of α_i equals 1 (Equation 4-1).

Equation 4-1. $x_i(0) = \alpha_i \delta \pi \lambda$

Where δ is the production yield, λ is the fabrication and manufacturing yield, and π is the new-scrap recycling loop factor.

Production encompasses the extraction, beneficiation, concentration, smelting, and refining processes that generate resource flows of sufficient purity for the subsequent fabrication and manufacturing processes. Wastes from the production processes may be stored in tailings, slag ponds, or landfills. Losses in primary production are only accounted for once in the model. The fabrication and manufacturing processes further transform resource flows into materials, semi-products, and products. Fabrication and manufacturing process residues, i.e., new scraps, may be collected for recycling (ξ) or lost ($1 - \xi$). Products remain in the use phase for each end-use sector depending on their lifetime distribution (ϕ) until they become obsolete. The use of applications may imply some dissipation (ω_i). It may be voluntarily induced to obtain the product's function, such as applying pesticides in agricultural fields. At the same time, the involuntary dispersion of metals to the environment may also occur, for example, due to corrosion (Lifset et al., 2012). Obsolete products may be collected as old scraps. The metals or materials they contain are generally either sorted and recycled into new material flows (γ_i), either incinerated and/or landfilled ($1 - \gamma_i$). Some obsolete products may also be abandoned in place or hoarded for some time before they enter the waste management system (Dewulf et al., 2021). Metals that enter the recycling streams may be either functionally, non-functionally recycled, or lost to slags or dusts (Graedel et al., 2011; UNEP, 2011). We consider the functional end-of-life recycling (θ) to include both closed and open-loop recycling where the inherent properties of the recycled are preserved, i.e., the physical and chemical properties that made the material desirable are retained after recycling in the new material flow (UNEP, 2011). Conversely, non-functionally recycled metals represent the portion of recycled metals that end up as tramp elements or impurities in the material stream in which they end up (Graedel et al., 2011). By extension, we also considered the downcycling of metals to low-value applications as non-functional recycling (e.g., copper elements contained in slags used in cement). Losses to recycling processes ($1 - \theta$) here include non-functional recycling on top of other losses. While landfilled and non-functionally recycled metals could theoretically be recovered at some point in the future (Beylot et al., 2020; Dewulf et al., 2021), they are here conservatively considered as losses (Helbig et al., 2020). Primary and secondary production are allocated to end-use sectors with the same factor α . The evolution of the cohort of metal at time $t > 0$ is modelled using transfer coefficients for each main life cycle processes as well as product lifetime distributions (Equation 4-2).

Equation 4-2. $x_i(t > 0) = \lambda \pi \theta \alpha_i \sum_j \gamma_j \sum_{t'=0}^{t-1} \phi_j(t - t') (1 - \omega_j) x_j(t')$

4.2.3 End use distributions

We modified and adapted the list of end-use sectors of Helbig et al. (2020) to represent the diversity of potential applications across the studied metals. We referenced 41 potential sectors with dedicated average lifetimes and distributions, reported as Weibull distributions. Sectors include large-scale construction, mechanical equipment, transport, and more specialized applications such as cutting tools and solar cells. Three end-use sectors are proposed to consider the diversity of batteries: consumer electronics & lead-acid, electric vehicles (including hybrid vehicles), and industrial batteries.

Similarly, two sectors are referenced for magnets: small (e.g., ferrite magnets used in various applications) and large magnets (e.g., large permanent magnets used in, e.g., wind turbines and magnetic resonance imaging). Moreover, multiple generic end-use sectors are included, covering a diversity of materials for which actual end uses are not precisely determined or undefined "other uses" sectors reported in the literature for many metals. Such materials include glass and ceramics, paint, and plastics. "Other uses" reported in the literature are split into four distinct categories based on the most common applications they include for each metal. The complete list of end-use sectors is provided in Annex B, along with the description of their lifetime distributions.

4.2.4 Data collection

A wide range of references were consulted to estimate or calculate transfer coefficients for each process yield, dissipation in use rate, as well as end-use distribution for each metal. These are detailed in Table B10 - Table B70 of Annex B. We here briefly describe the main data sources underlying the dataset. The MFAs underlying the article of Helbig et al. (2020) are of sufficient quality. The production, fabrication, and recycling yields calculated by the authors were re-used in the present article. These MFAs were available for aluminium (Bertram et al., 2017), chromium (Johnson et al., 2006), iron (Wang et al., 2007), cobalt (Harper et al., 2012), nickel (Reck and Rotter, 2012), copper (Glöser-Chahoud, 2017), zinc (Meylan and Reck, 2017), gallium (Licht et al., 2015), germanium (Licht et al., 2015), selenium (Kavlak and Graedel, 2013a), silver (Johnson et al., 2005), indium (Licht et al., 2015), tin (Izard and Müller, 2010), tellurium (Kavlak and Graedel, 2013b), tantalum (Nassar, 2017), tungsten (Meylan et al., 2015), rhenium (Meylan et al., 2015), and lead (Mao et al., 2008). Some modifications were required to obtain metal- and product-specific dissipation in use rates, collection and recycling yields. These are described in Annex B.

Multiple other material flow studies were consulted, such as the global MFAs for ten of the rare earth elements (Du and Graedel, 2011), scarce metals (Peiró et al., 2013) and antimony (Haarman, 2015),

and material flow analyses for the United States in 1998 realized by the United States Geological Survey (USGS, 2004), amongst others. Articles published as outcomes of the Criticality of Metals project lead by the Centre for Industrial Ecology of Yale University (Graedel et al., 2015; Harper et al., 2015; Nassar et al., 2012; Nuss et al., 2014; Panousi et al., 2016) were also significant to build this dataset. They provided insights on end-use distributions, production yields, and EOL-RR for numerous metals and applications. Moreover, a book chapter of Nassar (2013) was used to establish process yields for most platinum group metals. Finally, the works of Ciacci et al. (2015) provided most of the required information to calculate or estimate dissipation in use rates per metal and application.

Finally, end-use distributions were established for the most recent year or range of years possible. The previously cited MFAs, the documents from the Yale studies, the factsheets released as part of the European criticality studies (European Commission, 2020a, 2020b, 2014), the French geological survey (BRGM)'s criticality fact sheets (e.g., BRGM, 2018, 2017, 2016), and the yearly USGS's Mineral Commodity Summaries (e.g., that of 2020: USGS, 2020) provided insights for the global end-use distribution of multiple metals. Additionally, multiple industry reports were consulted, e.g., for gold (World Gold Council, 2021), lithium (SQM, 2019), magnesium (Wietlisbach, 2018), platinum group metals (Johnson Matthey, 2020a, 2020b, 2015), and silver (The Silver Institute, 2019).

4.2.5 Data availability and quality

In general, most complete information was available for major metals (iron, manganese, aluminium, copper, nickel, zinc, and lead), precious metals (gold, silver, and platinum group metals), and toxic metals (antimony, cadmium, chromium, mercury, and lead). A few other cycles were well documented, thanks to the available global MFAs (e.g., gallium, germanium, indium, selenium, and tellurium). Only partial data could be gathered from multiple sources for other metals, and estimations and assumptions were necessary to fill data gaps. The scarcest information was available for boron, holmium, lutetium, osmium, silicon, thallium, thulium, and ytterbium. Boron and silicon are used in relatively large amounts in the economy (over one Mt produced per year), highlighting the need to characterize their anthropogenic cycle better. Consequently, results are to be interpreted especially carefully for these metals. Nonetheless, it is possible to assert that these metals are currently mostly lost after just one application since no functional end-of-life recycling is known to occur. Data quality is taken into account in the semi-qualitative uncertainty assessment (described below).

4.2.6 Consistency and harmonization

While each metal was studied single-handedly, we ensured consistency across the studied metals in three ways. Firstly, we compared process yields and end-use distributions for metals used in the same large magnitude material flows to ensure that the reported values were reasonably correlated. For

example, iron and its principal alloying metals, i.e. chromium, manganese, niobium and vanadium, are used in various steel and stainless steel applications (Nuss et al., 2014). Secondly, we ensured that end-uses reportedly combining multiple metals at once, such as iridium-ruthenium catalysts, were aggregated in the same end-use sectors for each metal.

Thirdly, we used dedicated methodologies for three distinct groups of metals aiming to improve the quality of some of the available data, fill some data gaps and ensure additional harmonization across the studied metals: the 18 metals covered by Helbig et al. (2020), precious metals (especially platinum group metals), and rare earth elements including yttrium. Significant efforts were needed to estimate metal-specific production yields and end-of-life collection and recycling yields for rare earth elements. For the platinum group metals, a specific method was developed to flatten out the effects of the economic conjuncture on demand for investment products, which was also used for gold and silver used in investment products. The three group-specific approaches are detailed in Annex B.

4.2.7 Uncertainty

We evaluated uncertainty for each data point using a simplified semi-quantitative approach derived from the Pedigree matrix (Graedel et al., 2012; Weidema and Wesnæs, 1996). Five criteria were evaluated for each data point: reliability (U1), temporal correlation (U2), geographical and technological correlation (U3), corroboration (U4), and base and exogenous uncertainty (U5). Qualitative evaluations for each parameter allowed estimating geometric standard deviations (GSD) for each data using the Pedigree matrix. Beta distributions were then computed from GSD as they are defined within an interval of [0,1] that is well suited for process yields. Multivariate beta distributions (Dirichlet distributions) allowed accounting for the uncertainty of the end-use distributions. Uncertainty propagation was realized with a Monte Carlo simulation of 1 000 iterations allowing to define a 95% confidence interval on the computed in-use stocks over time and on the average lifetime of metals in the economy. The uncertainty rubric derived from the Pedigree matrix and the approach to compute uncertainty are detailed in Annex B.

4.2.8 Assumptions

Three main assumptions are made in the model. Firstly, the model results represent a contemporary assessment of the trends of losses of metals along their anthropogenic cycle, considering the current process yields and lifetime of applications, and not a prognosis (Helbig et al., 2020). While, in general, an increase of efficiency over time could be expected for some processes, there are other situations where yields may decrease. For example, this could be the case for the collection and sorting yield resulting from the miniaturization of electronic components for high-tech applications. Secondly, primary and secondary resources are assumed to have the same application share. Thirdly, the

fabrication and new scrap recovery yields are assumed to represent the current global yield. However, as cumulated in the single global fabrication yield, the share of different fabrication processes may have evolved along with end-use applications.

4.2.9 Limitations of the model

Aside from the main assumptions stated in the Methods section, some methodological choices imply possible limitations. Firstly, the selected end-use sectors may regroup diverse applications that have diverging lifetimes. It is possible that different metals used in the same end-use sector are used to a broader extent in some applications than in others, and therefore that the reported lifetime distribution does not precisely represent that of the metal reported in the category. For example, the electronics sector includes multiple applications such as laptops and mobile phones with different expected average lifetimes. Such variability could not be quantified and thus was not accounted for in the Monte Carlo simulation. Secondly, as noted in the methods section, both primary and secondary resources are attributed to the same share of end uses, which may not always represent reality. Thirdly, no lifespans are reported for life cycle phases other than the use phase. Finally, the model only provides an overview of total losses, and no distinction is made between the different loss stocks nor losses to the environment. Additional efforts are needed to categorize metals into more specific end-use applications, distinguish between primary and secondary metals, and identify where metal flows end up in more detail, as other authors have done for, e.g., steel (Pauliuk et al., 2017).

4.2.10 Projected in-use stocks and losses from recent production

We evaluated the evolution of in-use stocks and cumulative losses of metals over time linked with a recent cohort of produced metals. Global average production statistics were compiled for 2015-2019 based on World Mining Data (WMD, 2021). Data gaps were filled with complementary statistics from the U.S. Geological Survey for strontium and thallium (USGS, 2020), from the French Geological Survey for ruthenium (BRGM, 2020a), silicon (BRGM, 2019), hafnium (BRGM, 2018), osmium (Labbé and Dupuy, 2014), and iridium (BRGM, 2020b). The production of individual rare earth elements was estimated based on global rare earth oxide production from World Mining Data (WMD, 2021) and the share of individual rare earth elements produced as reported by the European Commission (European Commission, 2020a, page 663). The total extracted mass of metals was extrapolated using the production yield for each metal, and subsequent losses for the produced metals were determined with the losses for the production phase from the MaTrace dissipation model's results, as shown in Figure 4-3. Production statistics and process yields are provided in the Supplementary Data, along with in-use stocks from the recent yearly average production over the next 1 000 years.

4.3 Results and discussion

For the following analysis, metals are classified within four categories defined by the UNEP (2011) (cf. Figure 4-3). Ferrous metals comprise iron and its main alloying elements, primarily used in the construction, mechanical equipment, and transport sectors. Non-ferrous metals include most other bulk-produced metals (annual production over one Mt) that are typically used in similar sectors as ferrous ones and in electronics and various miscellaneous applications. Unlike UNEP's report, we also consider magnesia (magnesium) used as refractory materials for the steel industry and titanium oxides used in paint products (over 50% of their respective markets). Specialty metals englobe many technology metals used in, e.g., permanent magnets, batteries and electronics, and a wide range of miscellaneous applications. Precious metals consist of platinum group metals, most used as catalysts for the automotive industry and industrial processes, and silver and gold, mainly used in electronics, jewellery, and investment products.

4.3.1 Losses per life cycle phase

Figure 4-3 shows the average lifetime of metals in the economy as well as their shares of losses for the main life cycle phases.

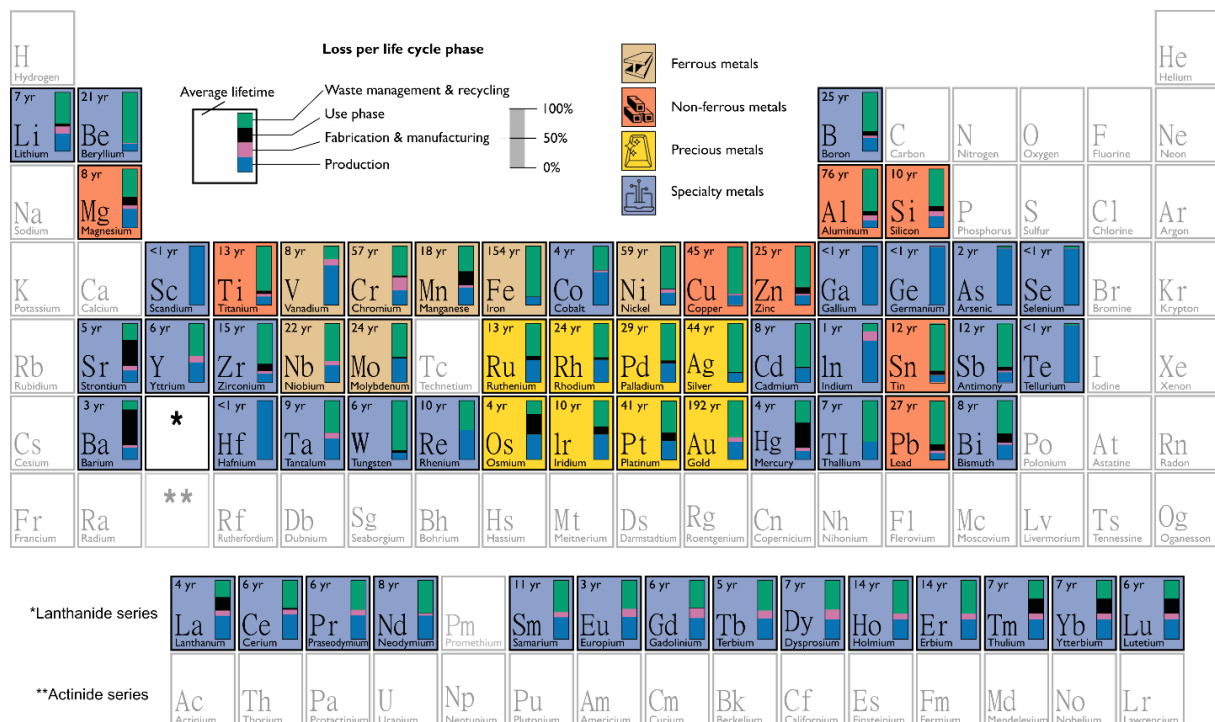


Figure 4-3. Distribution of metal losses per life cycle phase and lifetimes of metals in the economy

4.3.1.1 Production losses

Production processes often target only one or two metals in sufficient concentrations in the extracted ores, leaving aside other metals because they are not economically extractible. Production losses are

generally smaller amongst bulk-produced metals, which are also carrier metals in most cases. They are most important for 15 metals, 13 of which are specialty metals, the other two being vanadium and osmium. About 4 out of 16 Mt of extracted specialty metals are directly diverted to final disposal facilities during production. They reach over 30% of the total losses for rare earth elements (lanthanide series) and precious metals, 50% for cobalt, 70% for indium, and are greater than 95% for arsenic, gallium, germanium, hafnium, scandium, selenium, and tellurium. Production losses are proportionally smaller for precious metals, with about 6 out of 38 kt extracted, non-ferrous metals, with about 20 out of 140 Mt extracted, and ferrous metals, with about 0.23 out of 1.8 Gt extracted. Of the latter category, iron alone accounts for about 1.7 Gt extracted, out of which 0.2 Gt are lost to production.

4.3.1.2 Fabrication and manufacturing losses

Cumulative losses to the fabrication and manufacturing processes are the least important for 49 out of 61 metals. They are negligible for iron, and represent less than 1% of the cumulative losses of precious metals (0.35 kt). Proportionally, they become more important amongst specialty metals with 3% of cumulative losses (0.6 Mt), non-ferrous metals (6% of losses, with 9 Mt), and ferrous metals other than iron (7% of losses, with 5 Mt – of which 4 Mt are chromium). Most specialty metals undergo a single life cycle, explaining smaller losses to fabrication and manufacturing than other metals.

4.3.1.3 Use phase losses

Losses to the use phase are negligible for most metals. They represent around 2% of total losses by weight for ferrous metals (with 30 Mt; and 10% when disregarding iron, with 7 Mt). Likewise, about 2% of precious metals are lost during use (700 tons). Use losses are greater amongst non-ferrous metals (7% of losses, with 10 Mt) and represent as much as 31% for specialty metals (5 Mt). They are most prominent for a few metals voluntarily used in dissipative applications. Notable examples include oil and gas well drilling muds, representing about 80% of barium's and 30% of strontium's uses, and artisanal gold mining, which accounts for over one-third of mercury uses. Agricultural products account for about 5% of bismuth and 10% of magnesium use. Fluid cracking catalysts used in the petroleum industry represent about 5% of cerium and 45% of lanthanum oxides uses. About 3% of aluminium and 24% of manganese are used as deoxidization and desulfurization agents for steel production.

Moreover, involuntary losses contribute minimally to total metal losses. Given their nature, these losses are expected to mostly end up in the environment. For example, zinc-containing car tires and tungsten carbides used in cutting tools wear off during use, and some metals exposed to outdoors environment corrode (mainly ferrous and non-ferrous metals used in construction and automotive industries, e.g., galvanized steel).

4.3.1.4 Waste management and recycling losses

The lion's share of cumulative losses over time are due to waste management and recycling. They are most important for 43 metals. Waste management and recycling account for about 85% of losses of ferrous metals (1.49 Gt, 1.47 of which is iron), 80% for precious metals (31 kt), 71% for non-ferrous metals (100 Mt), and 40% for specialty metals (6 Mt). Metals undergoing multiple life cycles thanks to relatively efficient collection and recycling channels are still mostly lost to waste management over time, albeit over longer periods (e.g., aluminium, copper, gold, iron and platinum). Aside from closed-loop recycling of a few longer-lasting metals used in industrial applications (e.g. platinum alloys used in the glass industry), the yields of waste management processes (collection and sorting) seldom reach 90% and compare rather unfavourably to fabrication and manufacturing yields.

Moreover, recycling losses may occur during the remelting of alloys, as different metals tend to accumulate in dusts (e.g., zinc) and slags (e.g., chromium and vanadium) or end up as contaminants in large magnitude streams (e.g., copper in steel flows) (Reck and Graedel, 2012; Reuter et al., 2019; UNEP, 2011). Losses to recycling processes are most important for metals widely used in ferrous alloys (e.g., chromium, iron, manganese, molybdenum, and niobium), aluminium, and zinc, about half of which is used to protect steel from corrosion. Smaller remelting losses can be expected for pure metals. By weight, recycling losses are greater amongst ferrous metals (25% of total losses), and decreasingly important for non-ferrous (8%), precious (2%), and specialty metals (0.4%).

4.3.1.5 Lifetimes of metals in the economy

The contemporary lifetimes of metals range from less than a year (e.g., gallium and selenium) to just under two centuries for gold (Figure 4-3 and Figure 4-4). Higher process yields such as recycling rates and their use in applications with longer lifetimes both contribute to greater lifetimes. Generally, bulk-produced ferrous (chromium, iron, manganese, molybdenum, and nickel) and non-ferrous metals (aluminium, copper, lead, nickel, and zinc), as well as precious metals (gold, palladium, rhodium, platinum, silver), have higher lifetimes. Thus, average lifetimes are greater amongst non-ferrous (8 to 76 years, with an extracted mass-weighted average of 51 years), precious (4 to 192 years, with an extracted mass-weighted average of 61 years), and ferrous metals (8 to 154 years, with an extracted mass-weighted average of 151 years). Contrastingly, the lifetimes of specialty metals range from less than a year to 25 years, with extracted mass-weighted average of 12 years. Gold, and more importantly iron, pull up average lifetimes for precious and ferrous metals, respectively. The former represents 12% of the volume of precious metals extracted, but its lifetime of 192 years is at least four times higher than other precious metals. Iron accounts for 97% of the mass of extracted ferrous metals, and its lifetime is at least twice and a half that of other ferrous metals.

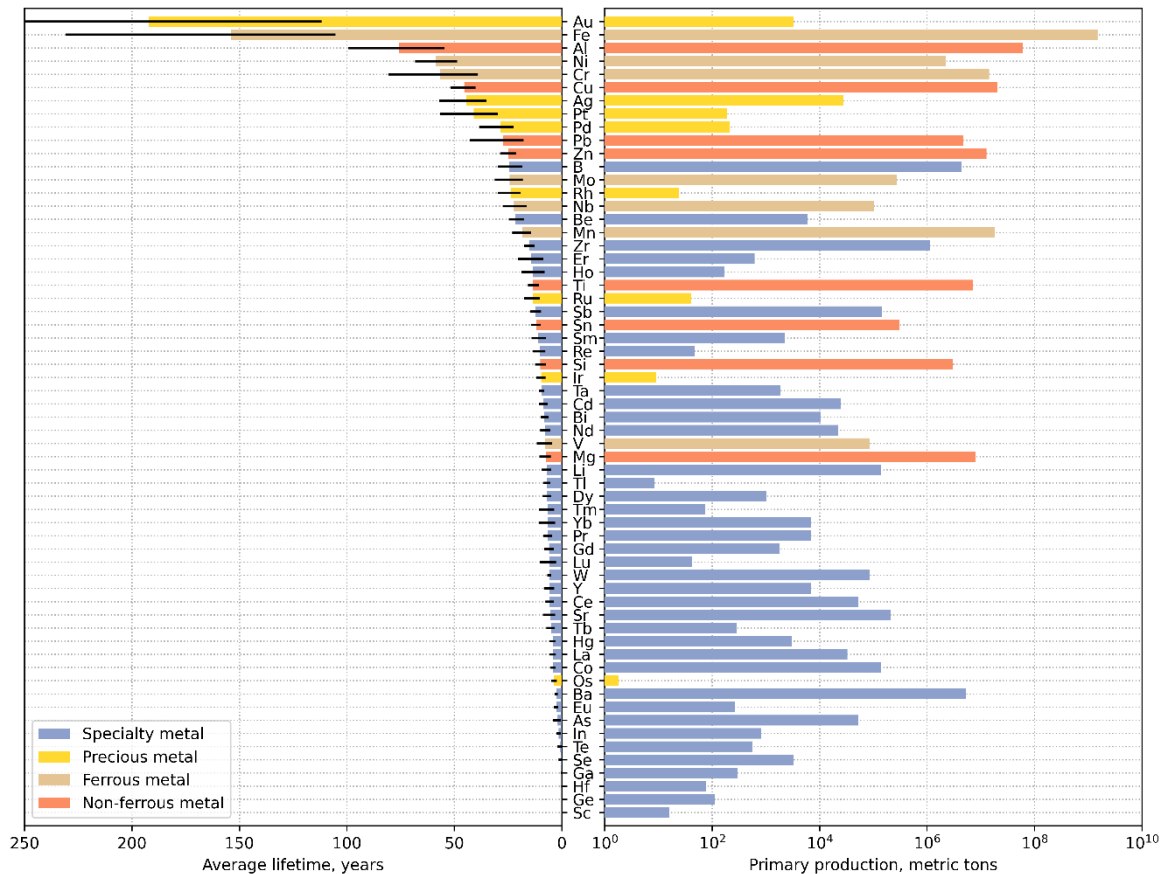


Figure 4-4. The average lifetimes of metals in the economy versus average annual production circa 2015-2019. The 95% confidence intervals for average lifetimes are indicated with black lines.

4.3.2 Losses over time

Here, we look at the fate of an average yearly cohort of extracted metals over time (Figure 4-5). The cohort is representative of average production statistics circa 2015-2019, as shown in Figure 4-4. Losses for ferrous, non-ferrous and precious metals are expected to occur over far longer periods than specialty metals. Most of the latter are lost within the first 25 years due to high losses in each life cycle phase, overall short application lifetimes, and negligible collection yields. The share of losses to the production and use phases are lower amongst other metal groups. Still, metals that remain in the economy for the longest see their share of losses to waste management and recycling increase over time. Indeed, these metals undergo multiple life cycles thanks to limited losses upstream in their life cycle before old scraps become available for recycling. Driven by the longevity of iron, about 0.13 Gt, 0.12 Gt, 0.21 Gt and 0.27 Gt of ferrous metals are lost to waste management in time intervals of 0-25, 25-50, 50-100 and 100-200 years, respectively. Approximately 32 Mt, 19 Mt, 19 Mt and 12 Mt of non-ferrous metals, and 10 kt, 7.5 kt, 6.9 kt and 3.8 kt of precious metals, are expected to be lost to waste management over these respective intervals. Recycling losses are proportionally most important for ferrous and non-ferrous metals: it is expected that about 0.03 Gt, 0.06 Gt, 0.09 Gt and 0.12 Gt of

ferrous metals, and 2.0 Mt, 2.0 Mt, 2.3 Mt and 1.6 Mt of non-ferrous metals are lost over these same periods.

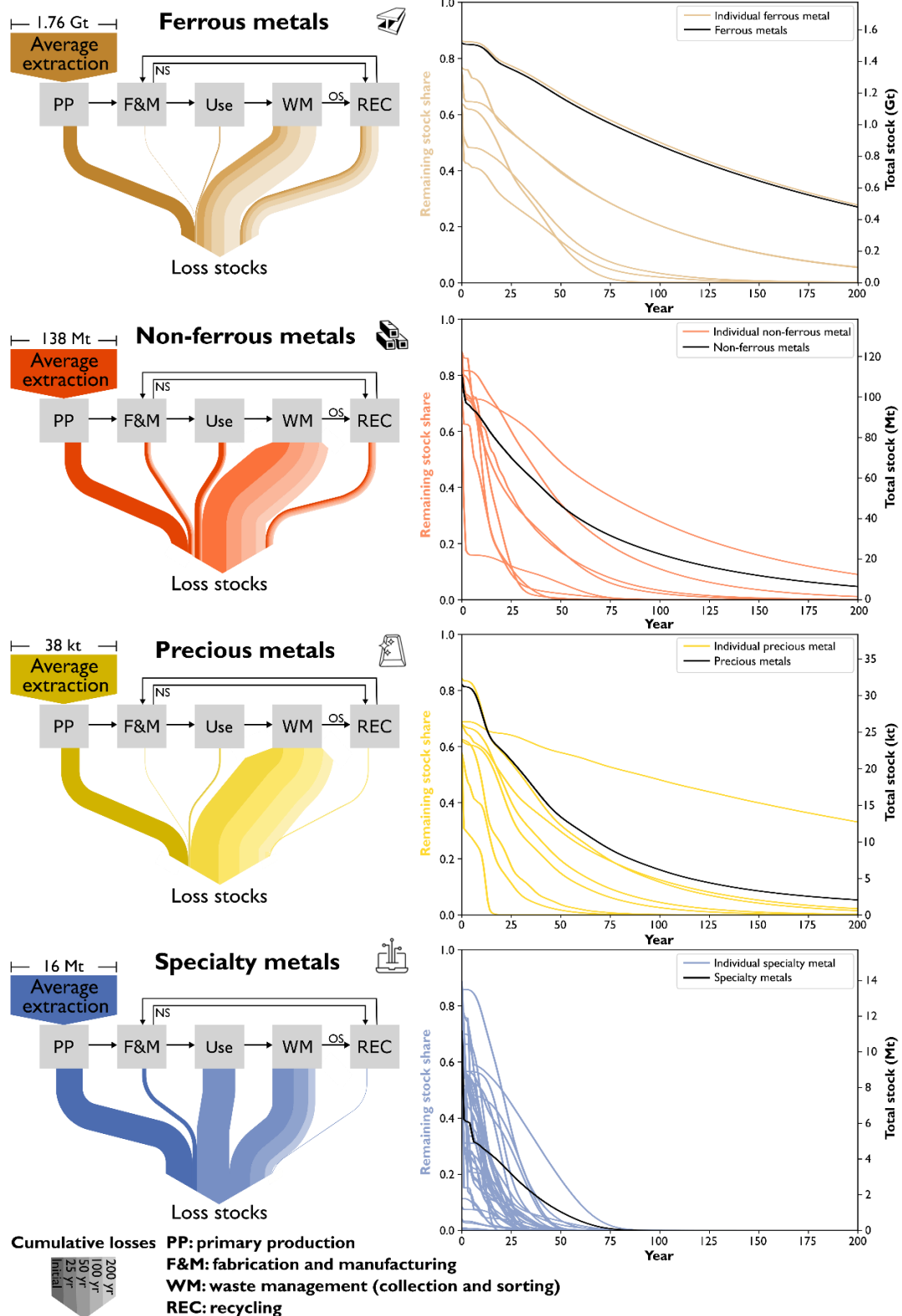


Figure 4-5. Predicted in-use stocks and losses of metals over two centuries. Graphs shown on the right hand side depict MaTrace results for individual metals (coloured curves, left Y-axis), and the total projected in-use stock from yearly extraction, per category (black curve, right Y-axis). Figure B3 to Figure B63 provided in Annex B present detailed graphs for individual metals.

About half of the total weight of recently extracted metals is projected to remain functionally in use in 100 years, most of which is iron. Specialty metals are expected to be completely lost by then. Disregarding iron, about 10% of ferrous, and 16% of precious and non-ferrous metals are expected to remain in use in 100 years. These shares respectively drop to 3%, 6%, and 7% in 200 years. Of all metals extracted recently, only about 5% of iron and 10% of gold are predicted to remain in the economy in 500 years.

4.3.3 Loss rates versus recycling indicators

The recycled content and end-of-life recycling rate (EOL-RR) are useful global indicators when setting up recycling strategies for metals (Reck and Graedel, 2012). However, they do not take a full life cycle perspective on identifying losses of metals over time. We compare our computed average loss rates with EOL-RR and recycled content statistics reported by the UNEP (2011) (Figure 4-6). The recycled content represents the total content of recycled metal entering the fabricated metal flow from both new and old scraps. In contrast, the EOL-RR is computed as the ratio between the volume of old scraps functionally recycled to that of old scraps generated: it solely depends on the collection, sorting, and recycling yields of old scraps (UNEP, 2011). The comparison should be interpreted carefully for magnesium and titanium because the UNEP's statistics only considered their metal forms, whereas the computed loss rates also include compounds of metallic elements such as magnesia used as a refractory material and titanium dioxide used in paint.

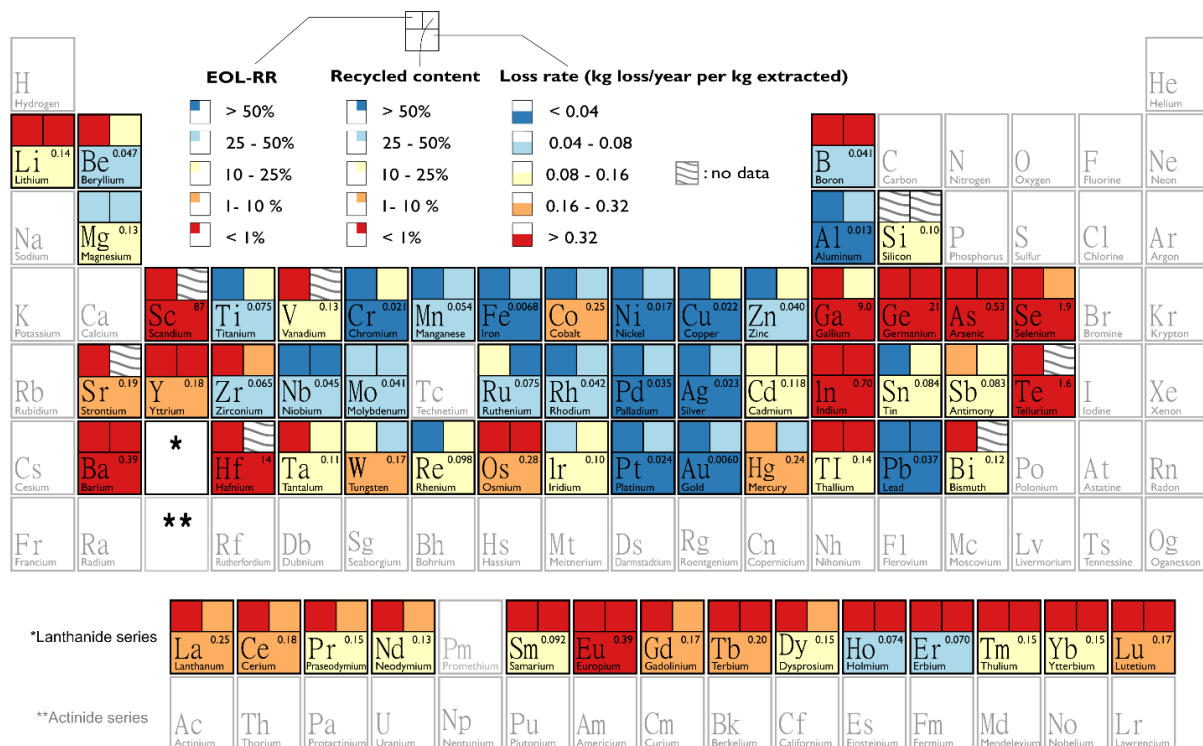


Figure 4-6. Loss rates versus EOL-RR and recycled content reported by the UNEP (2011)

EOL-RR tends to be greater than recycled content as the demand for most metals keeps increasing, requiring additional inputs from primary production (UNEP, 2011). Metals presenting a negligible EOL-RR and non-negligible recycled content suggest that their recycling content primarily originates from new scraps (UNEP, 2011). Generally, metals with higher EOL-RR and recycled contents also have lower loss rates. This is most apparent for ferrous and precious metals, highlighting the homogeneity of their end uses and relatively effective recycling channels. Metals presenting both high EOL-RR and high loss rate either undergo substantial losses before the end-of-life of their applications (e.g., during primary production or the use phase), or are used in short-lived applications. For instance, about 50% of cobalt is lost to production, and it is mainly used in applications with short lifetimes (e.g., batteries and catalysts), explaining its relatively high loss rate despite its reported EOL-RR of over 50%.

Loss rates of metals with lower EOL-RR are increasingly dependent on process yields amongst other life cycle phases and on the lifetime of applications in which they are used. Metals with similar EOL-RR might have divergent loss rates. In such cases, identifying where losses occur explain their loss rates (Figure 4-3). For instance, barium and tellurium both have a negligible EOL-RR and recycled contents, yet their loss rates diverge by a factor of about five. The former is mostly lost in the use phase, while tellurium is mostly lost during the production phase. Lastly, some metals with small EOL-RR also have loss rates competing with other relatively well-recycled metals because they are used in long-lived applications. For instance, despite its EOL-RR and recycled content of 0%, boron's loss rate is similar to that of rhodium. About half of boron is used in insulation-grade glass for the construction sector, with an average lifetime of 50 years in the model. In comparison, rhodium's EOL-RR is greater than 50% and its recycled content is between 25 and 50%; however, it is predominantly used for catalytic converters in car exhaust systems, with lifetimes less than half as long as the construction sector.

4.3.4 Discussion

The economy requires a continuous intake of metals: first, to meet the increasing demand for global development and upcoming technologies, and second, to regenerate the share of metals that is unavoidably lost in each cycle (Cullen, 2017; Reuter et al., 2019). Despite considerable challenges awaiting future mineral supply (Ali et al., 2017), the life cycles of most metals remain mostly linear today. Our study took a life cycle perspective on metal losses. We quantified these losses and attributed them to different life cycle phases over time, which may orientate appropriate responses to take for each metal. Our results suggest that, while losses are generally most important for the waste management and recycling phases, reducing losses in other life cycle phases may also be necessary to secure their supply and close their cycles.

Production losses are mostly linked with the economic feasibility of mining metals. Extractive industries only consider the potentially economically extractible fractions of ores as "mineral resources", and the share of mineral resources proven to be economically extractible become "mineral reserves" (CRIRSCO, 2019). Production processes target selected metals that are parts of reserves, while some of the potential by-products they contain and ores with lesser concentrations of metals are discarded as mining waste. This may lessen energy consumption of production and the associated costs in the short term, however resulting in a balance problem (Graedel, 2018): what should be done with metals that are not economically profitable to produce today yet are co-mined along with carrier metals? The current losses of by-products may increase shortage risks in the future because the opening and closing of metal mines typically depend on the geological occurrences and economic value of the carrier metal rather than that of by-products (Graedel, 2018). Increasing the recycling rate of a carrier metal or a sudden shift in its demand could reduce its primary production, with the rebound effect of lessening the accessibility to by-products (Løvik et al., 2016; Sprecher et al., 2017). Moreover, it should not be taken for granted that metals that are stockpiled in mine tailings and slags will be accessible in the future (Graedel, 2018). This may be most concerning for by-product metals increasingly used in emerging applications such as lithium-ion batteries (cobalt), permanent magnets (neodymium), solar cells (e.g., indium, gallium, germanium, selenium, and tellurium), and solid oxide fuel cells (scandium) (Marscheider-Weidemann et al., 2021). Moreover, thirteen out of fifteen metals lost most importantly during production are critical in the European Union (European Commission, 2020c) or the United States (Fortier et al., 2018), including the aforementioned cobalt, indium, gallium, germanium, scandium, and tellurium.

One way to improve production yields of by-product metals would be to redistribute a share of revenues from high value-added downstream sectors towards extractive industries to stimulate their production. Additionally, industrial reports usually include only the mineral resources or reserves, and losses of other metals may often go unseen. However, before the "what cannot be measured cannot be managed" comes the "what cannot be seen cannot be measured": enforcing a transparent reporting of ore compositions and unrecovered metals in each mining site, especially the largest ones, may be another step forward to predict supply capacity better (Mudd et al., 2017) and increase the production yields of these metals.

Losses of metals further down supply chains may be costlier for society, since more energy and efforts were spent on concentrating, transporting and transforming them (Chapter 2). Fabrication and manufacturing losses can be mitigated by collecting new scraps for recycling. New scraps of ferrous and non-ferrous metal are often collected, since they are generally clean from contaminants and their composition is known, making their collection and recycling easier than that of post-consumer scraps.

Those of precious metals are expected to be systematically collected given their important cost (UNEP, 2011). Addressing fabrication and manufacturing losses may become an increasingly practical means to increase circularity with increasing EOL-RR, as most metals currently undergo a single fabrication and manufacturing phase because they are not recycled from obsolete products.

Moreover, dissipative applications of metals should be avoided whenever possible, especially for toxic metals that remain in the environment. Losses to the environment are the most likely to be irreversible in comparison with those final waste disposal facilities. Yet, some uses that are dissipative are crucial to essential sectors (e.g., pesticides in agriculture) and may not always be totally avoided nor possibly substituted by other substances. Additional research is required to identify and measure dissipative flows of metals to the environment and prioritize corrective actions.

Lastly, the important losses to collection, sorting and recycling can often be explained by their prohibitive cost compared to primary production. Waste management and recycling industries currently favor the recovery of widely used ferrous and non-ferrous metals and valuable precious metals (Løvik et al., 2015; Velis and Brunner, 2013), leaving aside almost all specialty metals. The large variety of metals used in small amount in consumer products, their diversity, the complexity of composite materials, and their assembly lead to an increasing difficulty in effectively collecting, sorting, and recycling them. The greatest challenges to overcome to improve circularity for most metals remain improving designs of products as to ensure longer lifetimes and the recoverability and recyclability of materials they contain, and increasing their EOL-RR (Ciacci et al., 2015; Graedel, 2018; Moraga et al., 2021).

The design of products can impair the recovery of metals from obsolete products (Ciacci et al., 2015; UNEP, 2013), which is particularly evident for the recovery of metals from the latest short-lived technological applications resulting from rapid innovation. This constant innovation puts recycling channels in an odd situation where they seldom have time to develop strategies for existing applications when new generations of products arrive on the market. For instance, technical and economic constraints explain low collection and separation yields for metals that highly dispersed in applications, such as precious and specialty metals in electronic waste (Ari, 2016; Horta Arduin et al., 2019; UNEP, 2013, 2011). Thus, indicators of recyclability should be used at the product conception stage as to ensure compatibility between design decisions and installed recycling capacities. This would allow distinguishing between the shared responsibilities of product designers, waste management and recycling industries for the observed recycling rates.

Without regulations or economic incentives such as the Extended Producer Responsibility (OECD, 2001), market-driven production yields, product designs, and associated recycling yields can be

expected to perpetrate high amounts of losses and low lifetimes of metals. Systemic solutions remain to be widely implemented for most metals. Targets for improvements should be set along whole supply chains, and improvements monitored over time (Graedel, 2018). Our study and discussion reinforce the idea that governance is needed when it comes to managing mineral resources for sustainable development (Ali et al., 2017). Our results provide a more comprehensive insight into how well metals are retained in the economy than the EOL-RR and recycled content. Indeed, loss rates account for the lifetime of applications and other losses that are not straightforwardly apparent in recycling statistics, such as losses to primary production and to the use phase. Therefore, they may be a useful indicator to inform of how resource-efficient our economies are globally, and to support decision-making for reaching more resource efficient economies through targeted improvements of process yields and of product designs in different sectors.

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Chapter 5. Life cycle impact assessment methods for estimating the impacts of dissipative flows of metals

This chapter presents the conceptual framework and method development of two methods allowing characterizing the impacts of the dissipative flows (DFs) of mineral resources (metals). Methods follow the principles of option 2 presented in Chapter 3, and characterization factors (CFs) are computed based on the dynamic material flow analysis (MFA) results from Chapter 4. The dissipation of metals leads to potential environmental impacts, usually evaluated for product systems with the life cycle assessment (LCA) methodology. DFs of metals become inaccessible for future users, going against the common goal of a more circular economy. Therefore, they should be addressed in life cycle impact assessment (LCIA) in the area of protection (AoP) Natural Resources. However, life cycle inventory (LCI) databases provide limited information on dissipation as they only track emissions to the environment as elementary flows. Therefore, we propose two LCIA methods capturing the expected dissipation patterns of metals after extraction, based on the aforementioned dynamic MFA data. The lost potential service time (LPST) method provides precautionary indications on the lost service due to dissipation over different time horizons. The average dissipation rate (ADR) method distinguishes between the conservation potentials of different metals. Endpoint CFs are computed by introducing a price index, assumed to represent the potential value that metals hold for humans in the economy. The CFs calculated by these methods are meant to be applied to resource elementary flows in the LCI.

The introduction and methods sections presented in this chapter are excerpts from the following published paper: "Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G. (2021). Life cycle impact assessment methods for estimating the impacts of dissipative flows of metals. *J. Ind. Ecol. jiec.13136*. <https://doi.org/10.1111/jiec.13136>".

Additionally, the rationale and methods for computing endpoint CFs, as well as the resulting midpoint and endpoint CFs for 61 metals, originate from the following paper to be submitted: "Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G. (2021). Midpoint and endpoint characterization factors for mineral resource dissipation: methods and application to 6,000 data sets. To be submitted to *International Journal of LCA*." The discussion and conclusion are excerpts from these two articles.

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5.1 Introduction

DFs represent the real consumption of metals (Helbig et al., 2020). As discussed in Chapter 3, it is thus desirable to account for DFs in the LCI and characterize them with a consistent life cycle impact assessment (LCIA) method (Berger et al., 2020; Beylot et al., 2020b; Weidema et al., 2005; Zampori and Sala, 2017). However, accounting for DFs in inventories would imply important modifications of the existing LCI databases, which are not expected to be feasible in the short term (Beylot et al., 2020b, 2020a). Hence, in Chapter 3, we proposed two alternatives to account for DFs based on dynamic MFA data: either by updating or creating new LCIs (option 1), or by integrating the data on dissipation in an LCIA method that can be applied to extraction flows in the LCI (option 2).

We hereby propose a framework to take dissipation into account, with two LCIA methods which can be applied directly to extraction flows quantified in the LCI, as per the option 2 described above. We specifically address the impacts of DFs of metals on the AoP Natural Resources. The definition of DFs specific to this paper is provided in section 5.2.1. To achieve this, a concept and method to integrate time-differentiated measurements of DFs from dynamic MFA data is used to calculate CFs for 61 metals. The dynamic MFA data originates from Chapter 4. Dissipation patterns are integrated into CFs that can be applied directly to extraction flows quantified in the LCI. Two midpoint LCIA methods are developed: the lost potential service time (LPST) and the average dissipation rate (ADR). Their respective endpoint CFs are computed using a price index.

With regards to the overall structure of this chapter, the methods are presented in section 5.2, in which we explain the rationale for the methods (section 5.2.1), present the impact pathways addressing the fate of metals in the technosphere after extraction in terms of dissipation (section 5.2.2), justify the geographical scope and time horizons (section 5.2.3), and detail the calculations of the CFs (section 5.2.4). The CFs are computed using the results from Chapter 4. In section 5.3, we present and discuss the resulting midpoint and endpoint CFs. In section 5.4, we discuss the potential limitations of the developed methods. In section 5.5, a brief conclusion sums up the advances proposed in this chapter.

5.2 Methods

5.2.1 Rationale of the approach for the development of LCIA methods for dissipation

For clarity in the following text, we hereby provide definitions for dissipation-related terms. DFs are "flows to sinks or stocks that are not accessible to future users due to different constraints. These constraints prevent humans to make use of the function(s) that the resources could have in the technosphere. The distinction between dissipative and non-dissipative flows of resources may depend

on technological and economic factors, which can change over time." (Beylot et al., 2020b). The state of a resource which is considered as not accessible anymore is branded as "dissipated". An action which triggers DFs is characterized as "dissipative".

It can be said that dissipation generally goes against the commonly accepted objective of a more circular economy. While multiple conceptualizations and definitions of a circular economy exist (Kalmykova et al., 2018; Rizos et al., 2017), circularity is here defined as the capacity to keep resources in the economy as part of in-use stocks, in line with Moraga et al. (2021). In theory, a perfect circularity occurs when there are no DFs resulting from the anthropogenic cycle of metals (i.e. all processes have perfect yields of 100%), although there are intrinsic limits to reach perfect yields, such as thermodynamic limits due to the naturally growing entropy of systems and other technological or physical limits to processes (Cullen, 2017; Reuter et al., 2019). The yield of primary production can also be considered to influence the opportunity to make use of resources in the economy.

In this chapter, we consider DFs to be any flow of an element that is transferred to tailings and landfills, other material flows (through non-functional recycling), or emitted to the environment due to human activity. Non-functional recycling is defined as the *"portion of end-of-life recycling in which the metal is collected as old metal scrap and incorporated in an associated large magnitude material stream as a 'tramp' or impurity elements"* (UNEP, 2011). While it can generally be considered that the flows of most metals emitted to the environment become permanently inaccessible, some that are disposed of as final waste in landfills or tailings could be considered to be potentially accessible in the future (Moraga et al., 2021; Schneider et al., 2015, 2011; Stewart and Weidema, 2005; Zimmermann and Gößling-Reisemann, 2013). Still, elements ending in these stocks are not accessible to be made use of effectively in the economy at least for the duration they remain in them. Moreover, it is unsure whether or not they will at some point in the future become once again accessible, nor when this might be the case. Helbig and colleagues (2020) highlight that the recovery of elements from e.g. tailings and landfills is currently technically and economically unfeasible in the vast majority of cases. Moreover, Blengini et al. (2019) inventoried a relatively small number of implemented industrial projects recovering metals from these compartments. Hence, in this paper, such flows are considered as DFs based on precautionary principles, in line with the rationale of Zimmermann and Gößling-Reisemann (2013), which has been taken up by Helbig and colleagues (2020). More generally, such considerations are in line with the literature of life-cycle based studies which, in recent years, have increasingly accounted for DFs to final waste disposal facilities and other material flows in the technosphere (in which dissipated resources have low or no function), in addition to DFs to the environment (Beylot et al., 2020a, 2020b). Figure 5- presents an overview of DFs to the environment and to the technosphere for the main life cycle phases.

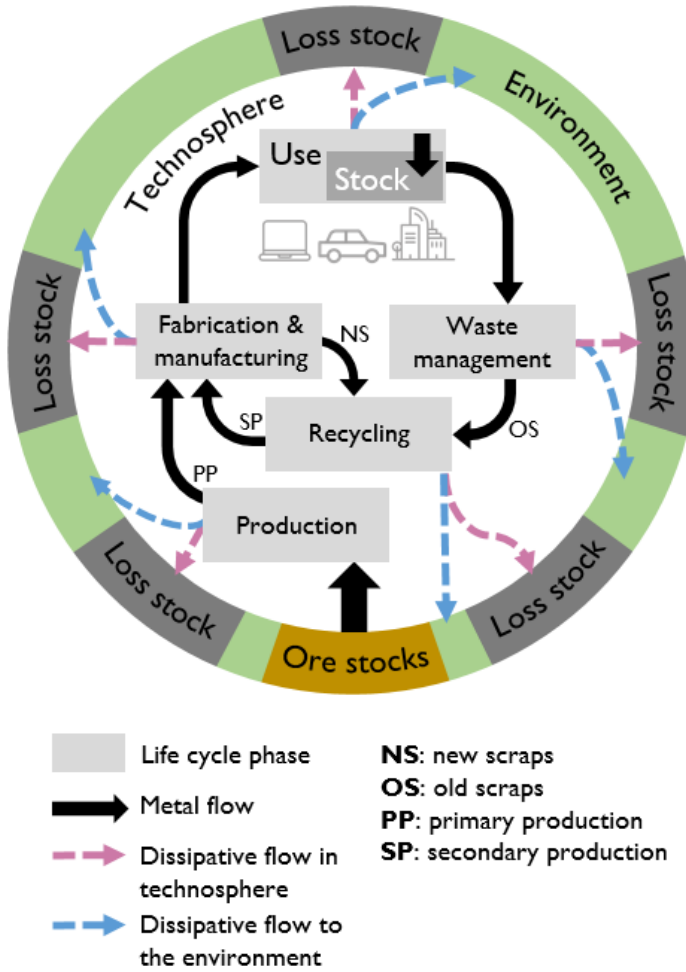


Figure 5-1. Anthropogenic cycle of mineral resources from the geological stock to temporary or final stocks and sinks through main life cycle phases and their corresponding dissipative flows (adapted from Figure 4-1).

Dotted pink arrows represent emissions to the environment, and dotted blue arrows represent either non-functionally recycled metals ending up in other material flows, or losses to final waste disposal facilities (landfills, slags and tailings storage facilities).

DFs can occur for each of the main life cycle steps: primary production, fabrication and manufacturing, the use phase, waste management, and recycling. Since flows to tailings and landfills are already accounted for as DFs, potential emissions from these two compartments are not further accounted for. One should note that the economy includes the resources whose functionalities are being made use of (i.e. in-use stocks), whereas stocks in the anthroposphere more broadly encompass resources stored in landfills and tailings in addition to in-use stocks.

Metals accumulate in anthropogenic stocks (e.g. in-use stocks, landfills) and sinks (e.g., non-functionally recycled metals in large magnitude flows, environmental compartments) while the geological ore stocks diminish with the cumulative extraction over time. As illustrated in Figure 5-1, the fate of metals in the technosphere depends on the yields of the successive processes as well as on the applications in which metals are used (see e.g. Ciacchi et al., 2015; Furberg, Arvidsson, & Molander,

2019; Zimmermann, 2017). The time dimension is crucial, as the DFs of metals will reach sinks and stocks depending not only on process yields, but also on the product lifetimes. For such reason, it is deemed critical to integrate time in circularity-oriented indicators (Moraga et al., 2021, 2019).

Since metal elements are indestructible, the highest potential instrumental value that a single element of metal can provide to human beings stems from a virtually permanent use of the element in the economy and at its maximum functionality (i.e. without a decrease of quality) (Ayres and Peiró, 2013). Functionality here refers to the contribution of metals to the instrumental value of in-use stocks in the form of products and services in the economy. In the LCA framework, the service provided by resources includes both the background services enabling a product system (such as energy, infrastructure, machinery and transport), and the functional unit related to the system under study.

The amount of service provided by metals and their potential value for users depend on the total in-use stocks of metals, on their quality, as well as on the applications in which they are used. The latter are intrinsically covered by the functional units in LCA. The two other factors, i.e. the total amount of in-use stocks and their quality, can be adversely impacted by human activities through two phenomena:

- DFs, going against circularity principles and resulting in a "lost potential to make use of the value of resources"
- The contamination of the material flow containing the metallic element, leading to a material of lesser quality and resulting in a "reduced or lost potential to make use of the value of resources". For example, impurities exceeding certain thresholds in aluminium alloys can affect their properties such as corrosion resistance (Davis, 2001). Most old aluminium scraps are recycled into cast alloys which in general have higher thresholds for alloying elements than wrought alloys (Classen et al., 2009).

5.2.2 Impact pathway and LCIA methods

We propose two methods to address the dissipation of metals: LPST and ADR. The studied impact mechanism is based upon the Service Time (ST) of resources, which is here defined as the service provided by a resource as part of in-use stocks in the economy after its extraction from the natural environment, and until it has been dissipated after one or successive applications. The total expected ST, ST_{TOT} , corresponds to the anthropogenic lifetime of resources as defined by Helbig and colleagues (2020). It depends on the yields of processes, dissipative uses, as well as the expected lifetimes of the different applications in which it is used.

The impact pathway addressing the lost potential to make use of metals once they have been extracted from the natural environment is described in Figure 5-2. The midpoint and endpoint CFs corresponding to different steps in the pathway are indicated on the figure.

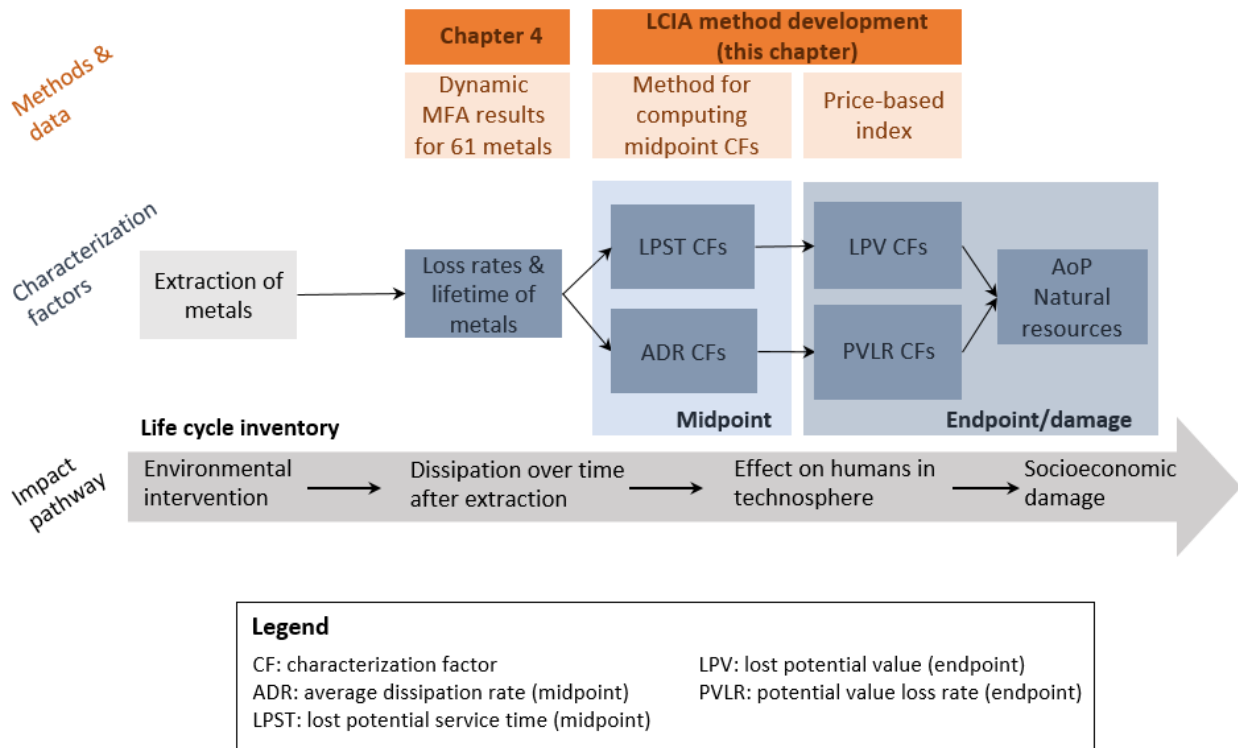


Figure 5-2. Impact pathways for the lost potential service time (LPST) and the average dissipation rate (ADR) methods

As illustrated in Figure 5-2, the LPST potentially induces a socio-economic impact for human beings, which could be assessed by quantifying any reduction or loss of the potential to make use of the value of extracted resources over time. It should be noted that many functions can be provided by a single resource. These functions can change over time (e.g. if copper in a pipe can be recycled in a wire), and each function could be valued differently by its users. At this point, additional research is needed to address this complex issue.

The fate of metals over their lifetime in the anthroposphere is the first step in the impact pathway, which corresponds to the expected ST of resources after extraction based on the current state of the economy. It is calculated based on the DFs of each life cycle phase and the lifetime of end-use applications, as presented in Chapter 4. The ST-integrated mass can be derived year by year based on the dynamic MFA data exposed in Chapter 4 and its related Annex B. The LPST can then be measured up to a desired time horizon, at which a cut-off may be placed. The ST_{TOT} can also be inverted in order to calculate the ADR. Detailed equations for each method are provided in section 5.2.4.

The LPST is proposed as a midpoint impact assessment method addressing the lost opportunity to make use of resources once they have been extracted from the lithosphere in relation to a distance-to-target approach, the target being perfect yields for all processes. We call this target the optimum service time (OST). This rationale is similar to that of other circularity-oriented approaches. For instance, Moraga and colleagues (2021) consider that the maximum in-use occupation is equal to the theoretical maximum use of materials within a given time horizon, while Parchomenko and colleagues (2020) also use a target system state for the measurement of the material effectiveness of circular economy strategies.

Figure 5-3 illustrates the concepts of ST and LPST at the time horizon cut-offs of 25, 100 and 500 years with an arbitrary dissipation curve for metal *i*. The grey area over the curve represents the lost ST that could have been provided by this same amount of extracted resources if no dissipation occurred over time. It is thus capped at 1 kilogram of metal *i* used in the economy per year per kilogram of metal *i* extracted.

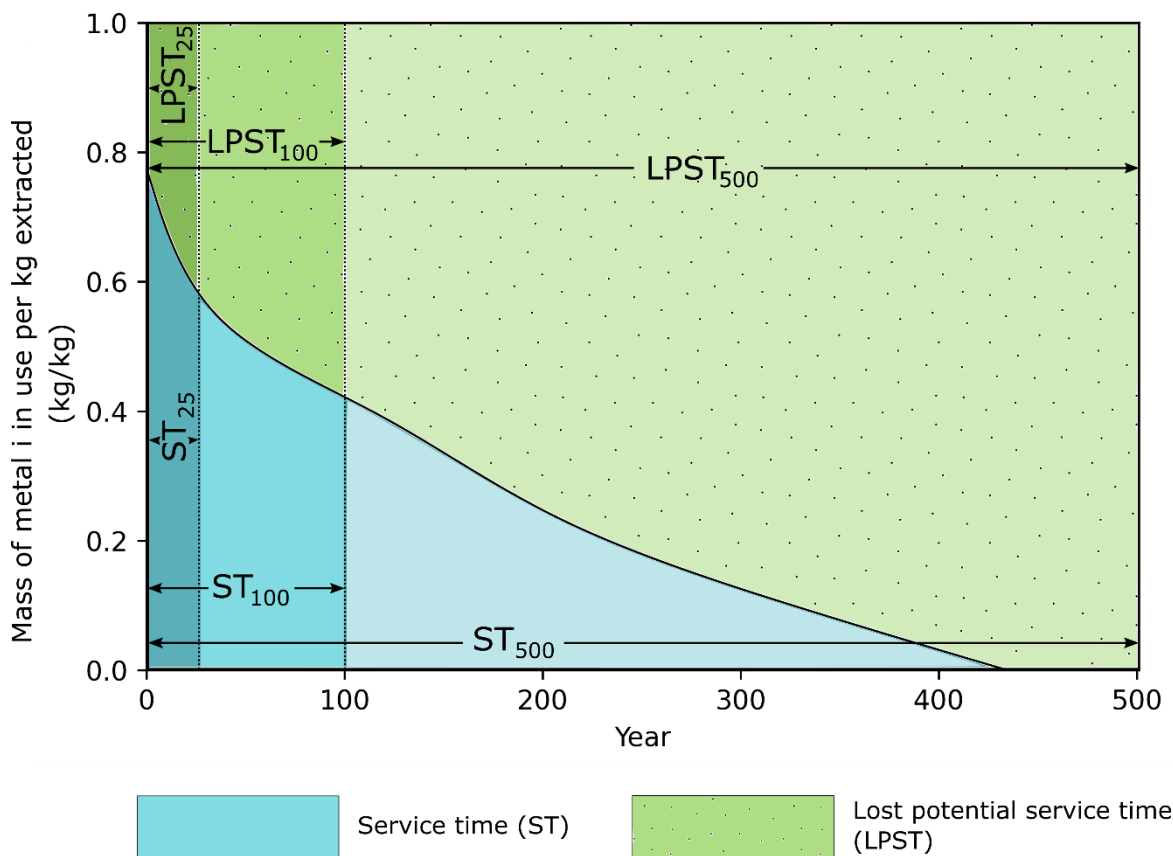


Figure 5-3. Example of an arbitrary dissipation pattern for metal *i* and the associated service time (ST_{TH}) and lost potential service time (LPST) at the time horizons 25, 100 and 500 years. The total expected service time (ST_{TOT}) corresponds to the whole blue area under the curve.

The initial mass of metal *i* is below 1 kg due to DFs that do not become part of in-use stocks, including losses to production and fabrication processes. The blue area under the curve represents the amount

of metal i in use over time (i.e., the ST) given the DFs of metal i that are expected to result from the successive processes and applications for an initial kg of metal i extracted from the ground. The ST thus represents the total amount of in-use functionality provided by a given amount of extracted resources up to a given time horizon. The total expected ST (ST_{TOT}) is equal to the integral of the dissipation curve until the metal is virtually completely dissipated. It has been calculated with a time horizon of 1 000 years (Chapter 4).

We also propose the ADR as a standalone indicator, which provides the global yearly dissipation rate of metals during their anticipated anthropogenic cycle. The ADR can be understood as a weighted average dissipation rate per year. The two proposed midpoint LCIA methods are intended to enable comparison between the global cycles of metals and to reflect their dissipation potentials within the current state of the economy. The midpoint CFs for the ADR method provide an information on how fast metals are dissipated on average, and those of the LPST method, show how much lost service can be attributed to the cumulated DFs over time.

Finally, as the last step of the impact pathway, it can be useful to evaluate the potential socio-economic impacts for humans due to the dissipation of different mineral resources (cf. Figure 5-2). The Joint Research Centre (JRC) of the European Commission suggested that prices can be used as a proxy to reflect the complex utility that resources have for humans, and are practical to do so since there the data is easily available (Beylot et al., 2020a). Indeed, some metals are scarcer, and/or more costly to produce than others. Higher priced metals are generally used in more specialized applications than cheaper ones, not only because of their scarcity or specific physico-chemical characteristics, but also because their high production cost does not justify their use in low value-added applications where they can be substituted for lower priced materials. For instance, gold is resistant to corrosion, but it is not used as a protective coating for steel reinforcement bars because zinc provides a similar function at a much lower price. The underlying assumption of using the prices of metals as an indication of their socio-economic value is that they reflect, albeit not perfectly (see discussion in, e.g., Beylot et al., 2020a; Ecorys, 2012; Henckens et al., 2016; and Huppertz et al., 2019), at least some extent of how valuable metals are to current and future society. We further assume that this value is maintained over time for as long as resources are not dissipated. The computation of the price-based weighting index accounting for the relative severity of dissipating different metals is presented in section 5.2.4.3.

5.2.3 Geographical scope and time horizons

It may be considered that the accessibility of resources at the global scale is of most relevance when assessing the impacts of resource use of the AoP, as these resources are often traded on international markets (Schulze et al., 2020). Our indicators are developed using the global scope.

Selecting the time horizon for the assessment must be done carefully, since it has implications on which generation is to be preferentially protected from environmental damage (Dyckhoff and Kasah, 2014; Sproul et al., 2019). Indeed, different stakeholders might be interested in various time horizons depending on what they value and on their beliefs about the adaptation potential of future societies (e.g. through technological developments) (Hofstetter, 1998). We discuss such considerations in Chapter 2.

Recently, both the SUPRIM project team and the JRC have proposed to account for the accessibility of resources over the short-term (25 years) and over a long-term time horizon (a few hundred years, e.g. 500 years in the SUPRIM project) (Beylot et al., 2020a; Schulze et al., 2020; van Oers et al., 2020). The JRC suggested taking a short term perspective of 25 years so that any flow of resources to the environment, final waste disposal facilities and products in use in the technosphere (with low-functional recovery) may be reasonably reported as dissipative (i.e. inaccessible to any future user within 25 years) (Beylot et al., 2021, 2020a). In the SUPRIM project, it was considered that dissipation results only from emissions to the environment in the long term, as anthropogenic stocks such as tailings and landfills may theoretically become accessible in the future (Schulze et al., 2020; van Oers et al., 2020). This assumption is optimistic about the future technical capacities and economic viability of recovering resources from these deposits and represents the best-case scenario. Moreover, it overlooks potential temporary accessibility issues due to e.g. geopolitics or economic cycles between the short and the long term. Hence, this assumption rather fits the individualist perspective, which is optimistic regarding technological solutions to support human adaptation (Hofstetter, 1998; Huijbregts et al., 2017). In contrast, we conservatively consider that all of the flows to these technosphere compartments remain inaccessible over any time horizon, which could be deemed the worst-case scenario. This may be viewed as most in line with the egalitarian perspective when assessing the impacts over longer time horizons (e.g. 500 years). Indeed, it is a precautionary assessment of the impacts for the future generations considering egalitarians' general aversion for burden shifting and pessimistic view of future technological developments (Hofstetter, 1998; Huijbregts et al., 2017).

In addition to the short-term (25 years) and long-term (500 years) time horizons, we propose a time horizon of 100 years for the midterm. Thus, the LPST method is computed for time horizons of 25, 100 and 500 years to reflect respectively the short-, mid- and long-term impacts of resource use, so that practitioners may choose that which corresponds more closely to the objectives of a given study. These options may allow to compare trade-offs between the impacts assessed with the LPST method and those assessed for other impact categories such as those included in the ReCiPe method (Huijbregts et al., 2017). However, it should be noted that the longer time horizons of 100 or 500 years may become

more representative of the hierarchist perspective only if some future recovery from tailings and landfills is considered, as they may believe in human adaptation through technological developments to a certain extent (Hofstetter, 1998; Huijbregts et al., 2017).

Moreover, it may be relevant to consider different time horizons when assessing the impacts of resource use on the AoP Natural Resources along with other methods. For instance, the LPST at a time horizon of 25 years may be complementary to the short-term depletion potentials as measured by the ADP economic reserves (van Oers et al., 2002), while the LPST at a time horizon of 500 years, to the long-term depletion potentials as measured by the ADP ultimate reserves (van Oers et al., 2019, 2002; van Oers and Guinée, 2016). Contrarily to the LPST method, the ADR method has no time horizon since it integrates the time function as part of its calculation in order to provide a yearly rate of dissipation.

5.2.4 Computation of the characterization factors

For the calculation of CFs, we consider 1 kg entering the (primary) production process instead of 100 units entering the use phase as in the model of Helbig et al. (2020). The nomenclature and symbols are the same as in the latter's work, except for "losses" which have been replaced with "DFs" for consistency within this chapter. The Supplementary Data spreadsheets provided with Chapter 4 show the dynamic MFA results used as inputs for the calculations of the midpoint CFs for the LPST method (CF_{LPST}) and the ADR method (CF_{ADR}) corresponding to the equations 5-1 to 5-8 presented below. Table 5-1 provides an overview of acronyms and symbols used in the equations.

Table 5-1. Acronyms, symbols, appellation, definitions and units

| Acronyms and symbols | Appellation | Definition | Unit |
|-------------------------|---|--|---------------|
| i | Metal <i>i</i> | Metallic elements, e.g. copper (Cu) | - |
| DF | Dissipative flow | Cf. section 5.2.1. | kg |
| msr_i | mass in service to mass extracted ratio | Measured ratio of metal <i>i</i> in service (in kg) at a given time <i>t</i> , in relation to 1 kg of metal <i>i</i> extracted | kg/kg = 1 |
| t | Time | Time lapse since extraction | yr |
| Δt | Time length | Time interval in between successive time periods <i>t</i> | yr |
| TH | Time horizon | Time horizon for the LPST indicator (25, 100 or 500 years) | yr |
| ST_{TH} | Service time | Anticipated service time of metal <i>i</i> until a given time horizon, for 1 kg of metal <i>i</i> extracted | kg.yr/kg = yr |
| ST_{TOT} | Total expected service time | Total expected service time of metal <i>i</i> in the economy after extraction and until its complete dissipation, for 1 kg of metal <i>i</i> | kg.yr/kg = yr |

| | | | |
|--------------------------|---|--|-----------------|
| | | extracted. For example, 1 kg of iron extracted provides an ST_{TOT} of 154 kg.yr. | |
| omsr | Optimal mass in service to mass extracted ratio | Theoretical optimal ratio between the mass in service in relation to 1 kg of metal <i>i</i> extracted, given perfect yields (1:1) | kg/kg = 1 |
| OST | Optimum service time | Theoretical optimum service time of metal <i>i</i> extracted until a given time horizon given perfect yields, for 1 kg of metal <i>i</i> extracted | kg.yr/kg = yr |
| LPST_{TH} | Lost potential service time | Total potential midpoint impacts due to the lost potential service time of metal <i>i</i> at a given TH for 1 kg of metal <i>i</i> extracted | kg.yr/kg = yr |
| CF_{LPST} | Characterization factors for the LPST method (midpoint) | Midpoint characterization factors for the LPST method: LPST of metal <i>i</i> in relation to the LPST of iron (Fe) at a given TH | kg Fe-eq./kg |
| TLPST | Total lost potential service time | Category total for the LPST method (midpoint) | kg Fe-eq. |
| LPV_{TH} | Lost potential value | Total potential endpoint impacts due to the lost potential service time of metal <i>i</i> at a given TH for 1 kg of metal <i>i</i> extracted | kg Fe-eq. |
| CF_{LPV} | Characterization factors for the LPST method (endpoint) | Endpoint characterization factors for the LPST method | kg Fe-eq./kg |
| TLPV | Total lost potential value | Category total for the LPST method (endpoint) | kg Fe-eq. |
| ADR | Average dissipation rate | Average dissipation rate of metals over their lifetime in the economy | kg/kg.yr = 1/yr |
| CF_{ADR} | Characterization factors for the ADR method (midpoint) | Midpoint characterization factors for the ADR method: ADR of metal <i>i</i> in relation to the ADR of iron (Fe) | kg Fe-eq./kg |
| TDR | Total dissipation rate | Category total for the ADR method (midpoint) | kg Fe-eq. |
| PVLR | Potential value loss rate | Characterization factors for the LPST method: LPST of metal <i>i</i> in relation to the LPST of iron (Fe) at a given TH | kg Fe-eq. |
| CF_{PVLR} | Characterization factors for the ADR method (endpoint) | Endpoint characterization factors for the ADR method | kg Fe-eq. |
| TPVLR | Total potential value loss rate | Category total for the ADR method (endpoint) | kg Fe-eq. |
| m_i | Mass of metal <i>i</i> extracted (inventory data) | Mass of metal <i>i</i> extracted in the LCI phase | kg |

5.2.4.1 Calculations for the LPST method (midpoint)

The fate of a given metal, i.e. the expected ST of metal *i* up to a given time horizon, is measured by summing its mass in service ratio (*msr*) over time up to the delimiting time horizon (*TH*) for 1 kg extracted, as depicted in Figure 5-3. It is calculated with Equation 5-1:

Equation 5-1. $ST_{i,TH} = \sum_{t=0}^{TH-1} msr_i(t) \cdot \Delta t$

where msr_i is the ratio of the mass of metal i in service at a given time t for 1 kg of metal i extracted in $\text{kg} \cdot \text{kg}^{-1}$, t is the time lapse since extraction in yr, TH is the time horizon (25, 100 or 500 years), and $\Delta t = 1\text{yr}$. ST is the anticipated service time provided by the initially extracted metal i until a given TH , expressed in $\text{kg} \cdot \text{yr} / \text{kg}$ of metal i extracted. The $ST_{i,TOT}$ is theoretically calculated with an infinitely large TH , and the model in practice was run with 1000 years of time lapse.

In the theoretical optimal conditions (i.e. with perfect yields), the optimal mass in service ratio ($omsr_i$) is of 1 kg in service for 1 kg extracted for each time step in Equation 5-1. Thus, each kg of metal i extracted provides 1 $\text{kg} \cdot \text{yr}$ of ST for each year t . The optimum service time (OST) for the initially extracted metal i until a given TH is calculated with Equation 5-2:

Equation 5-2. $OST_{TH} = \sum_{t=0}^{TH-1} omsr(t) \cdot \Delta t = omsr \cdot TH = 1\text{kg} \cdot TH / \text{kg}$

where $\Delta t = 1\text{yr}$. The OST is measured in $\text{kg} \cdot \text{yr} / \text{kg}$ of metal i extracted.

The LPST measures the difference between the target OST and the expected ST at a given TH for the same amount of extracted metal i , as shown in Equation 5-3:

Equation 5-3. $LPST_{i,TH} = OST_{i,TH} - ST_{i,TH}$

where the LPST is again measured in $\text{kg} \cdot \text{yr} / \text{kg}$ of metal i extracted. The LPST will always be smaller than the delimiting time horizon.

The characterization factors for the LPST method, CF_{LPST_i} , are calculated as the ratio between the LPST of metal i and the LPST of the reference substance iron (Fe) at a given TH . Fe was chosen as the reference substance because it proved to have the highest ST_{TOT} within the initial dynamic MFA for 18 metals of Helbig et al. (2020). Equation 5-4 provides the CF_{LPST} :

Equation 5-4. $CF_{LPST_{i,TH}} = LPST_{i,TH} / LPST_{Fe,TH}$

where the CF_{LPST} are given in $\text{kg Fe-eq.} / \text{kg}$.

The total impact score for dissipation as measured with the LPST method is named the total lost potential service time (TLPST). It is obtained by summing the mass of the flow of metal i extracted in the LCI (m_i , in kg) multiplied with their corresponding CF_{LPST_i} , for n metals covered in the method (i.e. 61 metals), as shown with Equation 5-5:

Equation 5-5. $TLPST_{TH} = \sum_{i=1}^n m_i \cdot CF_{LPST_{i,TH}}$

where the total lost potential service time, $TLPST$, is expressed in kg Fe-eq.

5.2.4.2 Calculations for the ADR method (midpoint)

The ADR is calculated with the inverse of the total service time ST_{TOT} of metal i , calculated with a hypothetical infinite time horizon (here calculated as 1000 years) and is therefore independent of the TH chosen for the LPST, as shown in Equation 5-6:

Equation 5-6. $ADR_i = 1/ST_{TOT_i}$

where ADR is measured in kg/kg.yr. The ADR can be understood as an average yearly dissipation rate, since the ST_{TOT} integrates the anthropogenic lifetime of metals given their time-dependent dissipation patterns. A mathematical demonstration backing up this claim is provided in Annex C. The ADR would take extreme values of only 0.001 kg/kg.yr if the ST_{TOT} was 1000 kg.yr/kg, and up to 52 kg/kg.yr if the ST_{TOT} was only a week.

The CFs for the ADR method, CF_{ADR} , are calculated with Equation 5-7:

Equation 5-7. $CF_{ADR_i} = ADR_i/ADR_{Fe}$

Where CF_{ADR} are measured in kg Fe-eq./kg.

The total potential impacts related to the expected dissipation rates of metals is obtained by summing the mass of the flow of element i extracted (m_i , in kg) with their corresponding CF_{ADR} , as shown in Equation 5-8:

Equation 5-8. $TDR = \sum_{i=1}^n m_i \cdot CF_{ADR_i}$

where the total dissipation rate, TDR , is measured in kg Fe-eq.

5.2.4.3 Calculations for endpoint characterization factors

Price statistics for most metals were compiled from USGS statistics by F. Ardente for that same JRC report (Beylot et al., 2020a), which were provided by F. A. and re-used here. These statistics were available for most metals from 1966 to 2015, and averages were computed over 10, 15, 20, 30 and 50 years (Beylot et al., 2020a). Given that the USGS provides single values for platinum group metals (PGMs) and rare earth elements (REEs), we complementarily compiled price data for single metals comprised in these two categories. We estimate that the more recent price statistics are most liable to represent current the value of resources for current technologies and bans on certain metals due to, e.g., toxicity. Hence, we considered the 10-year average price from 2006 to 2015 whenever possible. The 50-year average was considered when no 10-year average was available due to e.g. missing data in the underlying USGS statistics. This was the case for iron and niobium. Moreover, we

here considered the average price for iron and steel for the value of pure iron, which is difficult to assess because iron ores and pig iron are generally directly melted into steel.

In order to fill data gaps for PGMs and REEs, additional statistics were gathered. Please note that some of these statistics do not perfectly align with the 2006-2015 period considered for most other metals. Johnson Matthey's price charts were considered for PGMs, over the period 2006-2015 (Johnson Matthey, 2021). Additionally, osmium, for which no price data was available from the latter charts, was estimated to remain at a constant price of US\$400 per ounce (Labbé and Dupuy, 2014). Prices for single REEs were estimated from undisclosed price statistics compiled by the French geological survey (BRGM). As an indication, recent prices of REEs are available in a BRGM report (Bru et al., 2015, p. 151-158). Some are also and monitored by the German Mineral Resource Agency, along with other mineral resources (DERA, 2021). Price averages for REEs are computed over a 5-year period (2016-2020) as to avoid the important price peak of 2011 and the subsequent re-stabilization of prices due to Chinese bans on exports in the early 2010s (Bru et al., 2015). Finally, we estimated scandium's price based on the information that one kilogram of scandium oxides was worth US\$4600-US\$5400 between 2012 and 2018 (European Commission, 2020). All prices were inflation-adjusted to US\$1998, which is the reference value for USGS statistics.

We calculate the price index in an analogous way to the computation of price-based CFs in the method suggested by the JRC (Beylot et al., 2020a). To do so, we consider the 10-year average price of each metal (unless noted otherwise above) in comparison to that of iron, in US\$1998 per ton, as shown in Equation 5-9:

$$\text{Equation 5-9. } price\ index_i = \frac{average\ price_{i,US\$1998/t}}{average\ price_{Fe,US\$1998/t}}$$

Unlike the JRC approach that directly characterizes DFs identified in the LCI with price-based CFs (Beylot et al., 2020a), we multiply the price index with time-based midpoint CFs as to compare between the relative values of different metals for humans. We do not account for the uncertainty of price statistics, given that a large and unquantifiable uncertainty is linked with the assumption of the representativeness of the price index for their relative value for humans. The endpoint CFs for the ADR represent a potential value loss rate (PVLR) due to average dissipation rates, and are calculated as shown in Equation 5-10:

$$\text{Equation 5-10. } CF_{PVLR_i} = CF_{ADR_i} \cdot price\ index_i$$

Where CF_{ADVR_i} are measured in kg Fe-eq./kg.

Multiplying LPSTs with the price index provides an indication of the lost potential value (LPV) due to the inaccessibility of metals over time. It is assumed that the potential value of metals remains the same over time for as long as they are not dissipated, and therefore no discounting is applied. Endpoint CFs for the LPV are calculated as shown in Equation 5-11:

Equation 5-11. $CF_{LPV_i} = CF_{LPST_i} \cdot price\ index_i$

Where CF_{LPV_i} are measured in kg Fe-eq./kg.

The total impacts for the PVLR and LPV, i.e. the total PVLR (TPVLR) and total LPV (TLPV), are calculated analogously to their corresponding midpoint category totals, as shown in Equation 5-12 and Equation 5-13:

Equation 5-12. $TPVLR = \sum_{i=1}^n m_i \cdot CF_{ADVR_i}$

Equation 5-13. $TLPV = \sum_{i=1}^n m_i \cdot CF_{LPV_i}$

Where the TPVLR and TLPV are measured in kg Fe-eq. We insist that these values are expressed as iron equivalents: we do not aim nor pretend to measure absolute impacts in monetary terms. It could be an objective to measure absolute impacts in monetary terms (or with another unit of measurement) in future works in order to cumulate the impacts of dissipation with that of other resources and/or of ecosystem services. However, doing so will necessitate important additional method development and harmonization, as discussed in Chapter 2. Thus, for the time being, the computed endpoint CFs only allow comparing between the studied metals.

5.3 Results

Table 5-2 presents the ADR and LPST as well as their corresponding midpoint and endpoint CFs calculated for the ADR and LPST methods for 61 metals. The 95% confidence intervals for CFs, as depicted in Figure 5-4, Figure 5-5, Figure 5-6, and Figure 5-7, are provided in Annex D.

Table 5-2. Total expected service times (ST_{TOT} , corresponding to lifetimes in the economy calculated in Chapter 4), average dissipation rates (ADR, computed as loss rates in Chapter 4), lost potential service time (LPST) with time horizons of 25, 100 and 500 years, and the associated midpoint and endpoint characterization factors for the LPST and ADR methods

| | ST _{TOT} (Chapter 4) | ADR (Chapter 4) | LPST25 | LPST100 | LPST500 | Midpoint CFs | | | | Endpoint CFs | | | |
|------------|----------------------------------|--------------------|----------|---------|---------|-------------------|----------------------|-----------------------|-----------------------|--------------------|---------------------|----------------------|----------------------|
| | | | | | | CF _{ADR} | CF _{LPST25} | CF _{LPST100} | CF _{LPST500} | CF _{PVLR} | CF _{LPV25} | CF _{LPV100} | CF _{LPV500} |
| metal i | kg.yr/ kg | kg/ kg.yr | kg.yr/kg | | | kg Fe-eq./kg | | | | kg Fe-eq./kg | | | |
| 03_Li | 7.1E+0 | 1.4E-1 | 1.9E+1 | 9.3E+1 | 4.9E+2 | 2.2E+1 | 4.5E+0 | 3.0E+0 | 1.4E+0 | 1.1E+2 | 2.2E+1 | 1.5E+1 | 6.9E+0 |
| 04_Be | 2.1E+1 | 4.7E-2 | 7.7E+0 | 7.9E+1 | 4.8E+2 | 7.2E+0 | 1.9E+0 | 2.5E+0 | 1.4E+0 | 3.6E+3 | 9.3E+2 | 1.2E+3 | 6.7E+2 |
| 05_B | 2.5E+1 | 4.1E-2 | 1.1E+1 | 7.5E+1 | 4.8E+2 | 6.3E+0 | 2.6E+0 | 2.4E+0 | 1.3E+0 | 6.0E+0 | 2.5E+0 | 2.3E+0 | 1.3E+0 |
| 12_Mg | 7.5E+0 | 1.3E-1 | 2.1E+1 | 9.2E+1 | 4.9E+2 | 2.0E+1 | 5.0E+0 | 2.9E+0 | 1.4E+0 | 1.4E+1 | 3.4E+0 | 2.0E+0 | 9.4E-1 |
| 13_Al | 7.6E+1 | 1.3E-2 | 7.4E+0 | 4.9E+1 | 4.2E+2 | 2.0E+0 | 1.8E+0 | 1.6E+0 | 1.2E+0 | 5.8E+0 | 5.1E+0 | 4.5E+0 | 3.4E+0 |
| 14_Si | 1.0E+1 | 1.0E-1 | 1.6E+1 | 9.0E+1 | 4.9E+2 | 1.5E+1 | 3.9E+0 | 2.9E+0 | 1.4E+0 | 4.2E+1 | 1.1E+1 | 7.9E+0 | 3.8E+0 |
| 21_Sc | 1.1E-2 | 8.7E+1 | 2.5E+1 | 1.0E+2 | 5.0E+2 | 1.3E+4 | 6.0E+0 | 3.2E+0 | 1.4E+0 | 1.2E+8 | 5.3E+4 | 2.8E+4 | 1.2E+4 |
| 22_Ti | 1.3E+1 | 7.5E-2 | 1.2E+1 | 8.7E+1 | 4.9E+2 | 1.2E+1 | 3.0E+0 | 2.8E+0 | 1.4E+0 | 1.7E+2 | 4.5E+1 | 4.2E+1 | 2.1E+1 |
| 23_V | 7.7E+0 | 1.3E-1 | 2.0E+1 | 9.2E+1 | 4.9E+2 | 2.0E+1 | 4.8E+0 | 2.9E+0 | 1.4E+0 | 6.7E+2 | 1.6E+2 | 9.9E+1 | 4.7E+1 |
| 24_Cr | 5.7E+1 | 1.8E-2 | 9.7E+0 | 5.9E+1 | 4.4E+2 | 2.7E+0 | 2.3E+0 | 1.9E+0 | 1.3E+0 | 7.9E+0 | 6.8E+0 | 5.5E+0 | 3.7E+0 |
| 25_Mn | 1.8E+1 | 5.4E-2 | 1.6E+1 | 8.2E+1 | 4.8E+2 | 8.3E+0 | 3.8E+0 | 2.6E+0 | 1.4E+0 | 1.5E+1 | 6.6E+0 | 4.6E+0 | 2.4E+0 |
| 26_Fe | 1.5E+2 | 6.5E-3 | 4.1E+0 | 3.1E+1 | 3.5E+2 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 |
| 27_Co | 4.1E+0 | 2.5E-1 | 2.1E+1 | 9.6E+1 | 5.0E+2 | 3.8E+1 | 5.1E+0 | 3.1E+0 | 1.4E+0 | 1.8E+3 | 2.4E+2 | 1.4E+2 | 6.6E+1 |
| 28_Ni | 5.9E+1 | 1.7E-2 | 8.5E+0 | 5.7E+1 | 4.4E+2 | 2.6E+0 | 2.0E+0 | 1.8E+0 | 1.2E+0 | 6.6E+1 | 5.2E+1 | 4.6E+1 | 3.1E+1 |
| 29_Cu | 4.5E+1 | 2.2E-2 | 6.5E+0 | 5.9E+1 | 4.5E+2 | 3.4E+0 | 1.6E+0 | 1.9E+0 | 1.3E+0 | 3.0E+1 | 1.4E+1 | 1.7E+1 | 1.1E+1 |
| 30_Zn | 2.5E+1 | 4.0E-2 | 1.1E+1 | 7.6E+1 | 4.8E+2 | 6.2E+0 | 2.7E+0 | 2.4E+0 | 1.3E+0 | 1.8E+1 | 7.9E+0 | 7.1E+0 | 4.0E+0 |
| 31_Ga | 1.1E-1 | 9.0E+0 | 2.5E+1 | 1.0E+2 | 5.0E+2 | 1.4E+3 | 6.0E+0 | 3.2E+0 | 1.4E+0 | 8.5E+5 | 3.7E+3 | 2.0E+3 | 8.7E+2 |
| 32_Ge | 4.7E-2 | 2.1E+1 | 2.5E+1 | 1.0E+2 | 5.0E+2 | 3.3E+3 | 6.0E+0 | 3.2E+0 | 1.4E+0 | 5.6E+6 | 1.0E+4 | 5.4E+3 | 2.4E+3 |
| 33_As | 1.9E+0 | 5.3E-1 | 2.4E+1 | 9.8E+1 | 5.0E+2 | 8.2E+1 | 5.7E+0 | 3.1E+0 | 1.4E+0 | 6.5E+1 | 4.5E+0 | 2.5E+0 | 1.1E+0 |
| 34_Se | 5.3E-1 | 1.9E+0 | 2.5E+1 | 9.9E+1 | 5.0E+2 | 2.9E+2 | 5.9E+0 | 3.2E+0 | 1.4E+0 | 2.8E+4 | 5.7E+2 | 3.0E+2 | 1.4E+2 |
| 38_Sr | 5.4E+0 | 1.9E-1 | 2.0E+1 | 9.5E+1 | 4.9E+2 | 2.9E+1 | 4.9E+0 | 3.0E+0 | 1.4E+0 | 3.3E+1 | 5.6E+0 | 3.4E+0 | 1.6E+0 |
| 39_Y | 5.7E+0 | 1.7E-1 | 2.0E+1 | 9.4E+1 | 4.9E+2 | 2.7E+1 | 4.9E+0 | 3.0E+0 | 1.4E+0 | 1.0E+3 | 1.8E+2 | 1.1E+2 | 5.3E+1 |
| 40_Zr | 1.5E+1 | 6.5E-2 | 1.3E+1 | 8.5E+1 | 4.8E+2 | 1.0E+1 | 3.2E+0 | 2.7E+0 | 1.4E+0 | 1.5E+1 | 4.8E+0 | 4.0E+0 | 2.1E+0 |
| 41_Nb | 2.2E+1 | 4.5E-2 | 1.1E+1 | 7.8E+1 | 4.8E+2 | 6.9E+0 | 2.7E+0 | 2.5E+0 | 1.4E+0 | 2.0E+2 | 7.7E+1 | 7.1E+1 | 3.9E+1 |
| 42_Mo | 2.4E+1 | 4.1E-2 | 1.3E+1 | 7.7E+1 | 4.8E+2 | 6.3E+0 | 3.3E+0 | 2.4E+0 | 1.3E+0 | 2.9E+2 | 1.5E+2 | 1.1E+2 | 6.2E+1 |
| 44_Ru | 1.3E+1 | 7.5E-2 | 1.5E+1 | 8.7E+1 | 4.9E+2 | 1.2E+1 | 3.5E+0 | 2.8E+0 | 1.4E+0 | 6.3E+4 | 1.9E+4 | 1.5E+4 | 7.4E+3 |
| 45_Rh | 2.4E+1 | 4.2E-2 | 1.2E+1 | 7.7E+1 | 4.8E+2 | 6.5E+0 | 2.8E+0 | 2.5E+0 | 1.3E+0 | 5.1E+5 | 2.2E+5 | 1.9E+5 | 1.1E+5 |
| 46_Pd | 2.9E+1 | 3.5E-2 | 1.0E+1 | 7.3E+1 | 4.7E+2 | 5.4E+0 | 2.5E+0 | 2.3E+0 | 1.3E+0 | 9.6E+4 | 4.5E+4 | 4.1E+4 | 2.4E+4 |
| 47_Ag | 4.4E+1 | 2.3E-2 | 7.6E+0 | 6.2E+1 | 4.6E+2 | 3.5E+0 | 1.8E+0 | 2.0E+0 | 1.3E+0 | 2.7E+3 | 1.4E+3 | 1.5E+3 | 1.0E+3 |
| 48_Cd | 8.5E+0 | 1.2E-1 | 1.7E+1 | 9.2E+1 | 4.9E+2 | 1.8E+1 | 4.2E+0 | 2.9E+0 | 1.4E+0 | 7.6E+1 | 1.8E+1 | 1.2E+1 | 5.8E+0 |
| 49_In | 1.4E+0 | 7.0E-1 | 2.4E+1 | 9.9E+1 | 5.0E+2 | 1.1E+2 | 5.7E+0 | 3.1E+0 | 1.4E+0 | 7.8E+4 | 4.2E+3 | 2.3E+3 | 1.0E+3 |
| 50_Sn | 1.2E+1 | 8.4E-2 | 1.5E+1 | 8.8E+1 | 4.9E+2 | 1.3E+1 | 3.5E+0 | 2.8E+0 | 1.4E+0 | 3.6E+2 | 9.8E+1 | 7.8E+1 | 3.8E+1 |
| 51_Sb | 1.2E+1 | 8.3E-2 | 1.5E+1 | 8.8E+1 | 4.9E+2 | 1.3E+1 | 3.6E+0 | 2.8E+0 | 1.4E+0 | 1.3E+2 | 3.7E+1 | 2.9E+1 | 1.4E+1 |

| | ST _{TOT} (Chapter 4) | ADR (Chapter 4) | LPST25 | LPST100 | LPST500 | Midpoint CFs | | | | Endpoint CFs | | | |
|------------|----------------------------------|--------------------|----------|---------|---------|-------------------|----------------------|-----------------------|-----------------------|--------------------|---------------------|----------------------|----------------------|
| | | | | | | CF _{ADR} | CF _{LPST25} | CF _{LPST100} | CF _{LPST500} | CF _{PVLR} | CF _{LPV25} | CF _{LPV100} | CF _{LPV500} |
| metal i | kg.yr/ kg | kg/ kg.yr | kg.yr/kg | | | kg Fe-eq./kg | | | | kg Fe-eq./kg | | | |
| 52_Te | 6.3E-1 | 1.6E+0 | 2.4E+1 | 9.9E+1 | 5.0E+2 | 2.4E+2 | 5.9E+0 | 3.2E+0 | 1.4E+0 | 4.7E+4 | 1.1E+3 | 6.1E+2 | 2.7E+2 |
| 56_Ba | 2.6E+0 | 3.9E-1 | 2.2E+1 | 9.7E+1 | 5.0E+2 | 6.0E+1 | 5.4E+0 | 3.1E+0 | 1.4E+0 | 7.2E+0 | 6.6E-1 | 3.8E-1 | 1.7E-1 |
| 57_La | 4.1E+0 | 2.4E-1 | 2.1E+1 | 9.6E+1 | 5.0E+2 | 3.8E+1 | 5.1E+0 | 3.1E+0 | 1.4E+0 | 2.4E+2 | 3.3E+1 | 1.9E+1 | 8.9E+0 |
| 58_Ce | 5.6E+0 | 1.8E-1 | 2.0E+1 | 9.4E+1 | 4.9E+2 | 2.7E+1 | 4.8E+0 | 3.0E+0 | 1.4E+0 | 1.8E+2 | 3.1E+1 | 1.9E+1 | 9.0E+0 |
| 59_Pr | 6.5E+0 | 1.5E-1 | 1.9E+1 | 9.4E+1 | 4.9E+2 | 2.4E+1 | 4.6E+0 | 3.0E+0 | 1.4E+0 | 2.4E+3 | 4.6E+2 | 3.0E+2 | 1.4E+2 |
| 60_Nd | 7.8E+0 | 1.3E-1 | 1.7E+1 | 9.2E+1 | 4.9E+2 | 2.0E+1 | 4.2E+0 | 2.9E+0 | 1.4E+0 | 1.3E+3 | 2.8E+2 | 1.9E+2 | 9.2E+1 |
| 62_Sm | 1.1E+1 | 9.2E-2 | 1.5E+1 | 8.9E+1 | 4.9E+2 | 1.4E+1 | 3.5E+0 | 2.8E+0 | 1.4E+0 | 2.2E+2 | 5.6E+1 | 4.5E+1 | 2.2E+1 |
| 63_Eu | 2.6E+0 | 3.9E-1 | 2.2E+1 | 9.7E+1 | 5.0E+2 | 6.0E+1 | 5.4E+0 | 3.1E+0 | 1.4E+0 | 1.9E+4 | 1.7E+3 | 9.7E+2 | 4.4E+2 |
| 64_Gd | 5.9E+0 | 1.7E-1 | 1.9E+1 | 9.4E+1 | 4.9E+2 | 2.6E+1 | 4.6E+0 | 3.0E+0 | 1.4E+0 | 1.2E+3 | 2.2E+2 | 1.4E+2 | 6.6E+1 |
| 65_Tb | 5.1E+0 | 2.0E-1 | 2.0E+1 | 9.5E+1 | 4.9E+2 | 3.0E+1 | 4.8E+0 | 3.0E+0 | 1.4E+0 | 2.2E+4 | 3.5E+3 | 2.2E+3 | 1.0E+3 |
| 66_Dy | 6.8E+0 | 1.5E-1 | 1.8E+1 | 9.3E+1 | 4.9E+2 | 2.3E+1 | 4.4E+0 | 3.0E+0 | 1.4E+0 | 7.1E+3 | 1.4E+3 | 9.3E+2 | 4.4E+2 |
| 67_Ho | 1.4E+1 | 7.4E-2 | 1.3E+1 | 8.6E+1 | 4.9E+2 | 1.1E+1 | 3.2E+0 | 2.8E+0 | 1.4E+0 | 1.1E+3 | 3.0E+2 | 2.6E+2 | 1.3E+2 |
| 68_Er | 1.4E+1 | 7.0E-2 | 1.4E+1 | 8.6E+1 | 4.9E+2 | 1.1E+1 | 3.3E+0 | 2.7E+0 | 1.4E+0 | 4.5E+2 | 1.4E+2 | 1.2E+2 | 5.8E+1 |
| 69_Tm | 6.7E+0 | 1.5E-1 | 1.9E+1 | 9.3E+1 | 4.9E+2 | 2.3E+1 | 4.5E+0 | 3.0E+0 | 1.4E+0 | 7.3E+3 | 1.4E+3 | 9.3E+2 | 4.4E+2 |
| 70_Yb | 6.6E+0 | 1.5E-1 | 1.9E+1 | 9.3E+1 | 4.9E+2 | 2.3E+1 | 4.5E+0 | 3.0E+0 | 1.4E+0 | 1.7E+3 | 3.3E+2 | 2.2E+2 | 1.0E+2 |
| 71_Lu | 5.8E+0 | 1.7E-1 | 2.0E+1 | 9.4E+1 | 4.9E+2 | 2.6E+1 | 4.8E+0 | 3.0E+0 | 1.4E+0 | 4.7E+4 | 8.6E+3 | 5.3E+3 | 2.5E+3 |
| 72_Hf | 7.2E-2 | 1.4E+1 | 2.5E+1 | 1.0E+2 | 5.0E+2 | 2.1E+3 | 6.0E+0 | 3.2E+0 | 1.4E+0 | 1.1E+6 | 3.2E+3 | 1.7E+3 | 7.6E+2 |
| 73-Ta | 9.2E+0 | 1.1E-1 | 1.7E+1 | 9.1E+1 | 4.9E+2 | 1.7E+1 | 4.0E+0 | 2.9E+0 | 1.4E+0 | 4.0E+3 | 9.7E+2 | 7.0E+2 | 3.3E+2 |
| 74_W | 5.7E+0 | 1.7E-1 | 1.9E+1 | 9.4E+1 | 4.9E+2 | 2.7E+1 | 4.7E+0 | 3.0E+0 | 1.4E+0 | 1.3E+3 | 2.2E+2 | 1.4E+2 | 6.7E+1 |
| 75_Re | 1.0E+1 | 9.8E-2 | 1.7E+1 | 9.0E+1 | 4.9E+2 | 1.5E+1 | 4.0E+0 | 2.9E+0 | 1.4E+0 | 8.2E+4 | 2.2E+4 | 1.5E+4 | 7.5E+3 |
| 76_Os | 3.6E+0 | 2.8E-1 | 2.1E+1 | 9.6E+1 | 5.0E+2 | 4.3E+1 | 5.2E+0 | 3.1E+0 | 1.4E+0 | 1.4E+6 | 1.7E+5 | 1.0E+5 | 4.6E+4 |
| 77_Ir | 9.5E+0 | 1.0E-1 | 1.7E+1 | 9.0E+1 | 4.9E+2 | 1.6E+1 | 4.1E+0 | 2.9E+0 | 1.4E+0 | 3.3E+5 | 8.4E+4 | 5.9E+4 | 2.8E+4 |
| 78_Pt | 4.1E+1 | 2.4E-2 | 1.1E+1 | 6.6E+1 | 4.6E+2 | 3.8E+0 | 2.6E+0 | 2.1E+0 | 1.3E+0 | 1.7E+5 | 1.1E+5 | 9.3E+4 | 5.7E+4 |
| 79_Au | 1.9E+2 | 5.2E-3 | 7.6E+0 | 3.9E+1 | 3.3E+2 | 8.0E-1 | 1.8E+0 | 1.2E+0 | 9.4E-1 | 3.6E+4 | 8.1E+4 | 5.5E+4 | 4.2E+4 |
| 80_Hg | 4.2E+0 | 2.4E-1 | 2.1E+1 | 9.6E+1 | 5.0E+2 | 3.6E+1 | 5.0E+0 | 3.0E+0 | 1.4E+0 | 1.6E+3 | 2.2E+2 | 1.3E+2 | 6.2E+1 |
| 81_Tl | 7.0E+0 | 1.4E-1 | 1.8E+1 | 9.3E+1 | 4.9E+2 | 2.2E+1 | 4.4E+0 | 3.0E+0 | 1.4E+0 | 1.6E+5 | 3.2E+4 | 2.2E+4 | 1.0E+4 |
| 82_Pb | 2.7E+1 | 3.7E-2 | 9.7E+0 | 7.4E+1 | 4.7E+2 | 5.6E+0 | 2.3E+0 | 2.3E+0 | 1.3E+0 | 1.6E+1 | 6.7E+0 | 6.8E+0 | 3.8E+0 |
| 83_Bi | 8.0E+0 | 1.2E-1 | 1.7E+1 | 9.2E+1 | 4.9E+2 | 1.9E+1 | 4.1E+0 | 2.9E+0 | 1.4E+0 | 5.0E+2 | 1.1E+2 | 7.7E+1 | 3.7E+1 |

The midpoint CF_{LPST} and CF_{ADR} represent different readings of the global dissipation patterns after extraction. The CF_{LPST} provide an indication of the lost opportunity to make use of a single initially extracted kg of metal as part of in-use stocks in the economy with regards to a target of theoretical perfect yields. Higher CF_{ADR} indicate that, on average, a metal has a higher average dissipation rate and a shorter lifetime in the economy. For instance, the CF_{ADR} of chromium (Cr), which is relatively well conserved in the economy, is of 2.7E+0 kg Fe-eq./kg, while the CF_{ADR} of indium, which is relatively

rapidly lost after extraction, is of $1.1\text{E}+2$ kg Fe-eq./kg. Similarly, the LPST associated to these dissipation patterns reflect the lost opportunity to make use of metals (Figure 5-3). The corresponding CFs for, e.g., LPST100, are of $1.9\text{E}+0$ kg Fe-eq./kg for chromium and $3.1\text{E}+0$ kg Fe-eq./kg for indium. Using the LPST method may become more relevant if it is associated with the actual value of its use as part of an endpoint impact model, as suggested in section 5.2.2. On the other hand, the ADR rather focuses on losses occurring during the lifetime of metals and provides a direct reading of global dissipation rates, which makes it practical to use as a standalone indicator providing generic dissipation rates to compare metals. The CF_{ADR} have no specified time horizon because the expected lifetime of resources is integrated in the calculation of the ST_{TOT} .

Given the coverage of 61 metals, we may not provide extensive details for each of them. Instead, general trends per categories of metals (ferrous, non-ferrous, precious and specialty metals) are discussed below. Chapter 4 and its related Annex B should be consulted for detailed explanations on losses for each metal, underlying the computed midpoint CFs. The Supplementary Data provided with Chapter 4 shows all of the dynamic MFA results that underlay the calculation of midpoint CFs. For example, iron (Fe) is relatively well preserved in the economy compared to other metals, with an expected lifetime of 154 years thanks to relatively long-lived applications, a small percentage of dissipation in use, and a combined yield of about 80% for the collection and recycling processes (cf. Chapter 4). In comparison, gallium is mostly dissipated at the production phase (>99%) for technical and economic reasons (Helbig et al., 2020; Løvik et al., 2016, 2015). This results in relatively high midpoint CF values for gallium for the ADR, LPST25 and LPST100 methods ($1.4\text{E}+3$, $6.0\text{E}+0$ and $3.2\text{E}+0$ kg Fe-eq./kg, respectively). The endpoint CFs, computed using their price indexes, further denote the studied elements between each other based on their average prices, which is assumed to represent their value for humans. Figure 5-4 shows midpoint and endpoint CFs for the ADR method; Figure 5-5, those for the LPST25 method; Figure 5-6, those for the LPST100 method; and Figure 5-7, those for the LPST500 method.

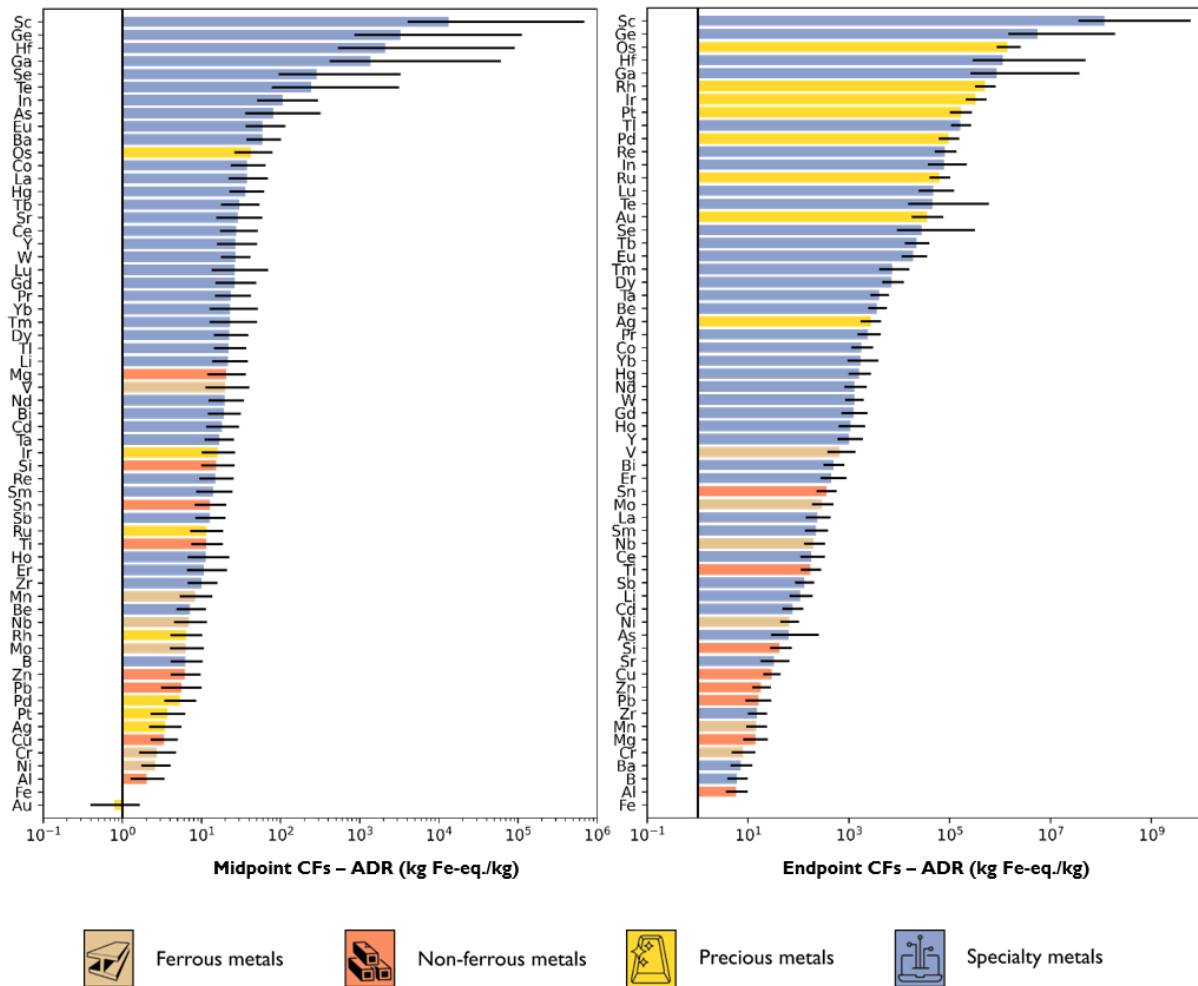


Figure 5-4. Midpoint and endpoint characterization factors for the ADR method. They are shown in ascending order and in log-scale to facilitate comparison between methods. Black lines indicate the 95% confidence intervals on the computed CFs resulting from the Monte Carlo propagation over 1 000 iterations. Colors represent the category of metals as established by the UNEP (2011). Average values for all CFs are shown in Table 5-2.

The highest CFs for the midpoint ADR method are almost entirely those of specialty metals, because they are typically dissipated the fastest. Endpoint CFs change dramatically for precious metals, whose price index are consistently amongst the highest. The latter are amongst the highest ranked CFs. Still, a few specialty metals that dissipate very rapidly and that have a relatively high market price, i.e., scandium (Sc), germanium (Ge), Hafnium (Hf), and gallium (Ga), remain amongst the top ranking CFs (1st, 2nd, 4th and 5th, respectively). Conversely, endpoint CFs for ferrous and non-ferrous metals remain in the bottom half of CFs ranking for both midpoint and endpoint.

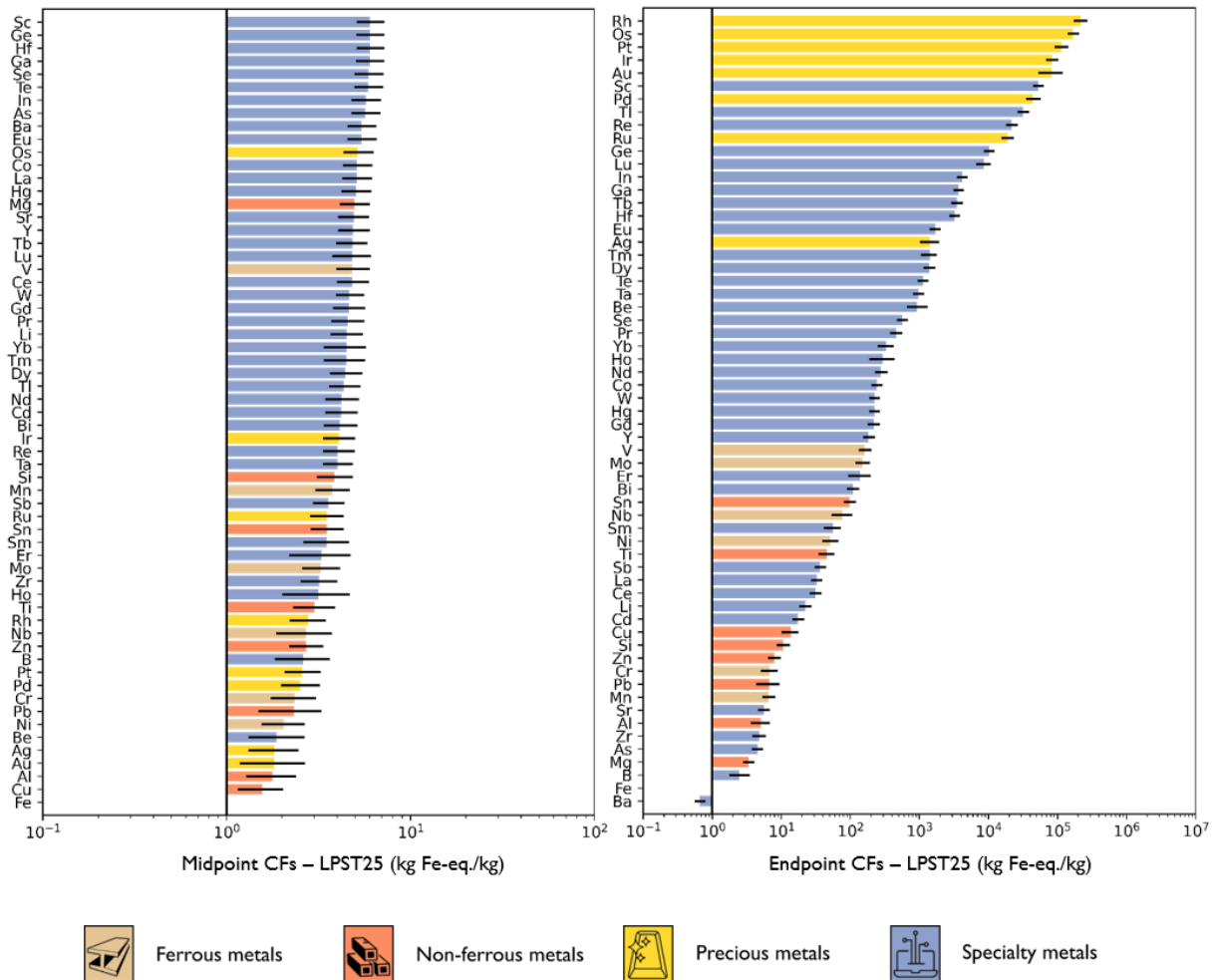


Figure 5-5. Midpoint and endpoint characterization factors for the LPST25 method. CFs are shown in ascending order and in log-scale to facilitate comparison between methods. Black lines indicate the 95% confidence intervals on the computed CFs resulting from the Monte Carlo propagation over 1 000 iterations. Colors represent the category of metals as established by the UNEP (2011). Average values for all CFs are shown in Table 5-2.

As for the ADR method, the highest CFs for the midpoint LPST25 method are almost entirely those of specialty metals, and endpoint CFs change dramatically for precious metals. The most rapidly dissipating metals coming up as top endpoint CFs in the ADR method are now less prominent in the ranking of CFs, and the top five CFs are consistently precious metals.

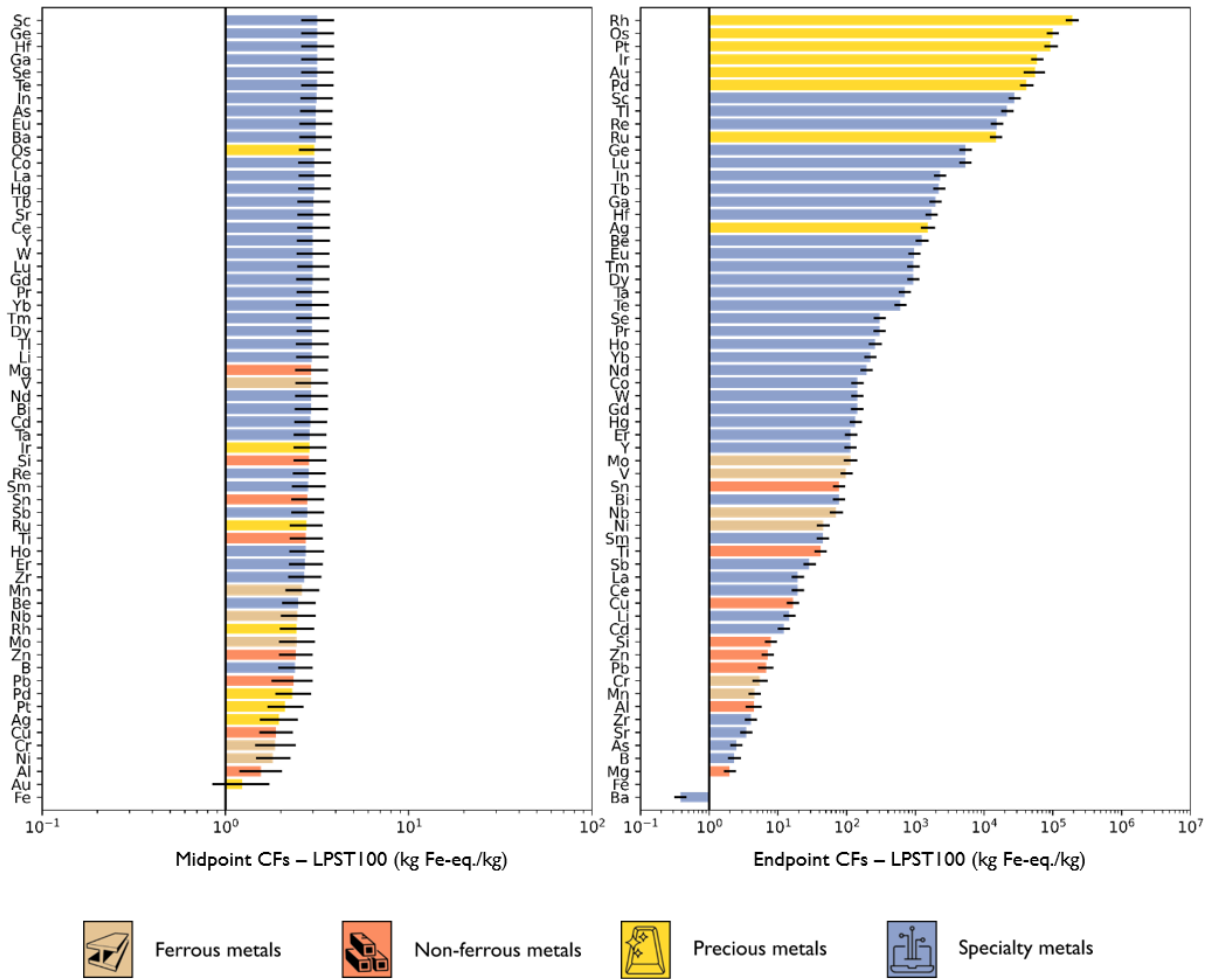


Figure 5-6. Midpoint and endpoint characterization factors for the LPST100 method. CFs are shown in ascending order and in log-scale to facilitate comparison between methods. Black lines indicate the 95% confidence intervals on the computed CFs resulting from the Monte Carlo propagation over 1 000 iterations. Colors represent the category of metals as established by the UNEP (2011). Average values for all CFs are shown in Table 5-2.

Similar trends as for the LPST25 midpoint and endpoint CFs can be observed for the LPST100 method. It can be observed that the price index has an increasingly important effect of the differentiation of endpoint CFs as the time horizon augments from 25 to 100 to 500 years (cf. also Figure 5-7), underlining that the lost potential value due to the DFs of higher prices metals increases as time goes.

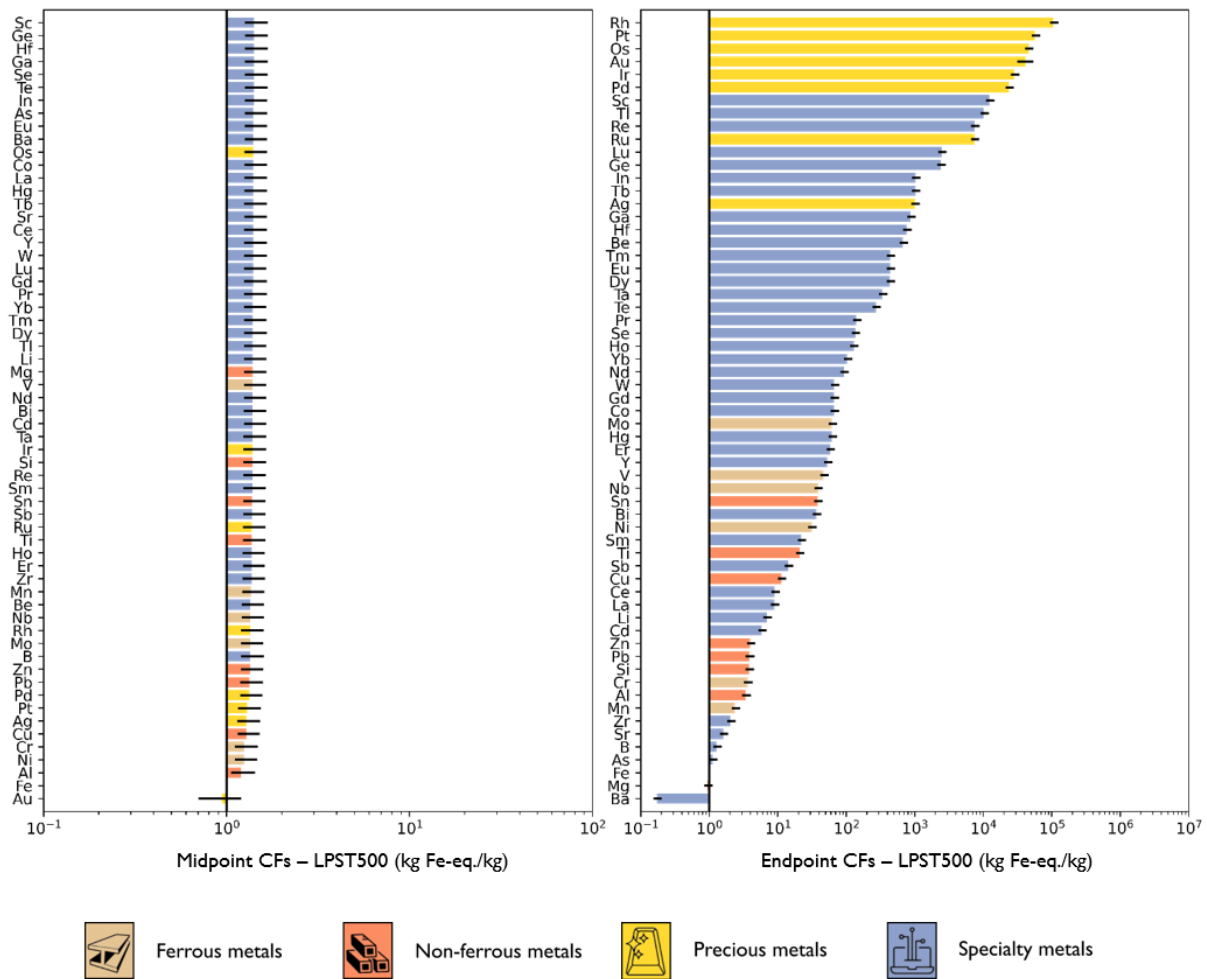


Figure 5-7. Midpoint and endpoint characterization factors for the LPST500 method. CFs are shown in ascending order and in log-scale to facilitate comparison between methods. Black lines indicate the 95% confidence intervals on the computed CFs resulting from the Monte Carlo propagation over 1 000 iterations. Colors represent the category of metals as established by the UNEP (2011). Average values for all CFs are shown in Table 5-2.

Overall, it can be observed that the relative ranking between substances is mostly identical between the midpoint ADR and LPST25, LPST100 and LPST500 methods. A few CFs have slight changes in their relative ranking because of the irregular shape of the ST curves due to long-lived applications (>25 years) or highly dissipative uses of a metal in its first applications (as it is the case for e.g. barium). The midpoint CF_{ADR} are rather well differentiated compared to the midpoint CF_{LPST} , which are increasingly similar over longer time horizons. This reveals that the ST_{TOT} of metals, resulting from both the lifetime of applications and the yields of processes for each of them, are highly influent on the CF_{ADR} , while the CF_{LPST} are also strongly influenced by the length of the time horizon. Indeed, as most studied metals are dissipated rather rapidly after their extraction, the yearly LPST is increasingly similar for all metals until they are completely dissipated, at which point they increase equally for each subsequent year. This explains why the CF_{LPST} are less distinct over longer time horizons.

The average values of midpoint CFs for the ADR method spread over 5 orders of magnitude, with $8.0\text{E}-1$ kg Fe-eq./kg for gold (Au) to $1.3\text{E}+4$ kg Fe-eq./kg for scandium (Sc). The CFs for the ADR method provide more distinction between elements, and CFs for the LPST method become less distinctive over longer time horizon. Hence, little to no distinction can be made between midpoint CFs for the LPST100 and LPST500 methods when uncertainty is taken into account.

It can be observed in Figure 5-4 to Figure 5-7 that adding the price index for the computation of endpoint CFs has a great influence on the CFs of metals and on their relative ranking. Metals with similar dissipation profiles, e.g., gold and iron, become differentiated after the price index is applied to compute endpoint CFs. For instance, when disregarding uncertainty, gold's midpoint CF is the lowest of all 61 metals because it is best retained in the economy; however, its endpoint CF increased by a factor of 44 621 (i.e., its price index), becoming the 22nd highest. Meanwhile, iron's CF remains amongst the lowest CFs in the endpoint (3rd lowest, after barium and magnesium) due to its low price index of 1.

The average value for the midpoint CFs for the LPST100 method only range from 1 to 3.2, whereas its endpoint CFs spread over 5 orders of magnitude. The CFs for the endpoint LPST25 method range over 7 orders of magnitude, i.e. from $6.6\text{E}-1$ kg Fe-eq./kg for barium (Ba) to $2.2\text{E}+5$ kg Fe-eq./kg for rhodium (Rh). Similarly, those for the endpoint LPST500 method range over 7 orders of magnitude, from 0.17 kg Fe-eq./kg for barium (Ba), to $1.06\text{E}+05$ kg Fe-eq./kg for rhodium (Rh). The endpoint CFs for the ADR method also become more differentiated than its midpoint CFs: they spread over 8 orders of magnitude, i.e. from 1 kg Fe-eq./kg for iron (Fe) to $1.18\text{E}+08$ kg Fe-eq./kg for scandium (Sc). Therefore, impact hotspots can be expected to be most acute using the endpoint ADR method.

The application of the price index to compute endpoint CFs increases the differentiation amongst CFs of the ADR method than amongst those of the LPST method, because midpoint CFs for the former are more differentiated to begin with. Metals that dissipate very quickly and that have a relatively high price index are more emphasized with the ADR method. For instance, scandium, which has the highest midpoint CF_{ADR} , CF_{LPST25} , CF_{LPST100} , and CF_{LPST500} , also has the highest endpoint CF_{PVLR} (ADR method), whereas its endpoint CFs for the LPST25, 100 and 500 methods rank 6th or 7th highest.

5.4 Limitations

5.4.1 Limitations of the midpoint characterization factors

The LPST and ADR methods offer a simplified solution to account for dissipation using current LCI, as suggested for the short-term agenda to account for dissipation in LCA proposed by Beylot et al. (2020b). However, the methods present some limitations due to the workaround framework that was

developed to anticipate dissipation and its impacts based on extraction flows in the inventories. Firstly, in the case where extraction data comes from LCI databases using allocation procedures, there could be an alignment (i.e. double counting, or discounting) between the allocation of primary production to multiple product systems in the database and the recycling considered for the calculation of the CFs. Secondly, global average yield values for all supply chains and applications making use of an element are considered in the computation of CFs, providing averaged values which are element-specific rather than application-specific. These may differ from the actual process yields considered in the LCI databases. Thirdly, as the CFs are meant to be applied to extraction flows, the results provide no specific differentiation between the processes that contribute most to the dissipation of metals along the life cycle of a specific product system.

These limitations may prove to be restrictive for the applicability of the proposed methods depending on the practitioner's objectives for a given LCA study. We insist that, when dissipation patterns for the different metals are well-known by the practitioner for a specific process or product system, it is likely that foreground data would allow to calculate dissipation potentials that contradict those suggested in our generic global model. In this situation, practitioners could prefer to calculate their own CF values based on their own product lifetime and DFs rather than use the CFs developed for our methods. The computational structure and model provided with Chapter 4 provide a useful basis to do so. Moreover, other process-centric approaches such as suggested by the JRC (Beylot et al., 2020a), or product-centric assessments such as the approach proposed by Moraga and colleagues (2021) could also provide alternatives to address dissipation as defined in this chapter, i.e. including DFs occurring within the technosphere. The approach suggested by the JRC is detailed and its operationalization in LCI databases is discussed with an application to a case study in Beylot et al. (2020a) and Beylot et al. (2020c). Yet, any potential routine application of that approach may require large-scale changes of LCI databases, justifying the development and use of interim approaches such as those developed in this chapter. Finally, all the aforementioned limitations ultimately support the need for detailed information on DFs made available in LCI before the dissipation of minerals can be operationalized in a consistent LCIA framework, as suggested by the JRC (Beylot et al., 2020b; Zampori and Sala, 2017).

Moreover, we would like to highlight that there might be a mismatch between what is defined and considered as a resource in widespread LCI databases and the ADR and LPST methods, especially concerning the potentially co-produced elements (e.g. gallium). Such problem has already been highlighted regarding the definition of mineral resources of the mining industry, which may differ from that used in different LCIA methods (Drielsma et al., 2016). Indeed, in the ADR and LPST methods, all of the extracted elements are accounted for, in line with the proposition of the Life Cycle Initiative's taskforce on mineral Resources (Berger et al., 2020), whereas the industry may consider

uneconomically extractible elements in a given context as valueless rock (gangue), and thus not as a resource per se (CRIRSCO, 2019; Drielsma et al., 2016). For instance, LCI databases such as ecoinvent consider resources to be the targeted elements in the ore when the mineral ore is valued only for its metal content (Classen et al., 2009; Weidema et al., 2013), which seems to somewhat align with the definition of resources of the mining industry. However, some elements contained in the ores that are not valuable economically today could potentially be so in the future. For example, gallium (a by-product of aluminium production) is overabundant in aluminium ores today in comparison to the current demand; however, an increasing demand for gallium along with a lower primary production of aluminium could lead to an insufficient production capacity of gallium in the future (Løvik et al., 2016, 2015). Thus, efforts should be spent on clearly identifying what are considered as resources in the LCI databases and how these resources compare to the definition of resources in the AoP Natural Resources. This investigation could allow to identify which flows of elements are to be considered as DFs, and eventually to allocate the impacts of dissipation to the processes that are actually responsible for these DFs (e.g. the aluminium production process may be responsible for DFs of gallium).

5.4.2 Limitations of the endpoint characterization factors

We here discuss limitations of using a price index to compute endpoint CFs. Indeed, while prices were considered to be overall useful to provide an estimate of the value of metals for humans, using the price-based index involves some limitations. First, the prices of metals include production costs that may distort the information of how actually valuable metals are to humans. We decided to maintain this information for the price index because there is not much information available on the share of production costs on the price of most metals (Huppertz et al., 2019), and because we estimated that the efforts put into production also partly reflect the utility of metals for humans. Second, the small demand for potential by-products may both lead to low production yields and high prices because of their high production cost. Low production yields in turn lead to highly dissipative profiles and related midpoint CFs, and high prices, to even higher endpoint CFs. In this case, there may be the strongest distortion in the assumed correlation between cost and value for human beings. Third, some unquantified uncertainty on endpoint CFs may also arise from using price data from different sources, for metals of possibly different qualities or purities, and in a few cases, over different time series. Nonetheless, we recommend utilizing endpoint CFs given the useful distinction that the price-based index provides between lower and higher value metals. Still, the aforementioned limitations should be kept in mind when interpreting impact assessment results.

5.5 Conclusion

A conceptual framework to address dissipation of abiotic resources in LCA, based on Chapter 3, was developed into concrete LCIA methods. CFs were computed with the dynamic MFA results obtained in Chapter 4. This demonstrates that (1) it is possible to uptake data obtained from other fields of research such as MFA to fill information gaps in the LCA framework, (2) the information can be used in an impact assessment method, and (3) an impact assessment method can provide information on the degree of circularity of a global metal cycle. As previously stated, the objective of the ADR and LPST methods is to provide a solution to overcome limited knowledge on the dissipation patterns of metals in LCA, because much of the DFs as defined in this paper can occur within the technosphere and are not tracked in LCI databases.

Moreover, conceptual advances relating the dissipation of resources to the AoP Natural Resources have been proposed with the concept of ST in the technosphere, which could be complemented with quality aspects of resources. The ST could also eventually be aligned with the lost service provided by ecosystems in the ecosystem services framework (see discussion on ecosystem services in e.g. Maia de Souza, Lopes, Hansson, & Hansen, 2018; Rugani et al., 2019).

Using the LPST or the ADR methods, designers and LCA practitioners can anticipate how the composition of their products (i.e. quantities and types of metals) influences the potential impacts of their system due to the potential dissipation. Still, the aforementioned limitations of the developed methods should be kept in mind. Future research could aim to increase the coverage of mineral resources that are configurations of elements such as fluorite (CaF_2), graphite (carbon) or to adapt the model to assess the dissipation of fossil fuels and their derivative products (e.g., plastics), and perhaps even that of biotic resources used in similar sections of economic activity as mineral resources (e.g., wood). Moreover, efforts could be spent at improving the evaluation of endpoint damage due to the dissipation of mineral resources by differentiating between their economic value and value in use (cf. discussion in Chapter 2).

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Chapter 6. Application of characterization factors to 6,000 life cycle inventory data sets

This chapter presents an application study investigating how the developed characterization factors (CFs) for the average dissipation rate (ADR) and lost potential service time (LPST) methods can be expected to influence impact assessment results in life cycle assessment (LCA) studies. To do so, we apply CFs developed in Chapter 5 to metal resource flows from 6,000 market data sets in the ecoinvent database. The data sets are grouped by sections of economic activity in order to provide some indications on how impact results could be expected to turn out for different sectors. The impact assessment results are compared with those for widely used methods: the abiotic depletion potential (ADP) and the ReCiPe 2016 methods.

This chapter is largely based on the following paper to be submitted: "Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G. (2021). Midpoint and endpoint characterization factors for mineral resource dissipation: methods and application to 6,000 data sets. To be submitted to International Journal of LCA."

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6.1 Introduction

In previous chapters, we presented how the impact pathway for the dissipation of mineral resource use related to the area of protection (AoP) natural resources (Chapter 2), we proposed a framework to evaluate the impacts of dissipation of mineral resources based on dynamic MFA data (Chapter 3). We then computed dynamic MFAs for 61 metals (Chapter 4), and proposed midpoint and endpoint CFs to assess the impacts of dissipation of mineral resources based on the results from these MFAs (Chapter 5). The aim of Chapter 6 is now to investigate how impact assessments linked with the dissipation of mineral resources, as calculated with the midpoint and endpoint CFs of the ADR and LPST methods, can be expected to turn out in LCA studies, and to compare these results with those of widely used LCIA methods. To do so, we study the impact assessment results for midpoint and endpoint CFs from the ADR and LPST methods that are applied to a large amount of data sets. We also investigate how this assessment compares with that using the abiotic depletion potential (ADP) ultimate reserves method (van Oers et al., 2019, 2002), as well as those of the surplus ore potential (SOP) (Vieira et al., 2017) and surplus cost potential (SCP) (Vieira et al., 2016) included in the ReCiPe2016 method (Huijbregts et al., 2017). Materials and methods are presented in section 6.2. Results and analysis are exposed in section 6.3, and a conclusion is provided in section 6.4.

6.2 Materials and methods

For this application study, we consider the midpoint and endpoint CFs for the LPST and ADR methods (Chapter 5), the latest ADP ultimate reserves method based on the cumulative production in 2015 that is recommended by its authors (van Oers et al., 2019, 2002), as well as those of the midpoint (SOP) and endpoint (SOP) methods included in ReCiPe 2016 (Huijbregts et al., 2017). We considered the hierarchist CFs for the latter method. The ADP ultimate reserves is currently recommended for use in the PEF (Zampori and Pant, 2019). The ADP ultimate reserves and SOP methods are recommended by the Life Cycle Initiative to answer different questions linked with mineral resource use (Berger et al., 2020). The former is recommended to answer the question "How can I quantify the relative contribution of a product system to the depletion of mineral resources?", and the latter, interim recommended to answer the question "How can I quantify the relative consequences of the contribution of a product system to changing mineral resource quality?". In comparison, the ADR and LPST methods address could address the question "how can I quantify the relative contribution of a product system to the dissipation of mineral resources?". For a comparison between more LCIA methods addressing mineral resource use, we refer readers to the study of Rørbech et al. (2014) and to the critical review of the Life Cycle Initiative's taskforce on mineral resources (MR taskforce) (Berger et al., 2020; Sonderegger et al., 2020). Rørbech et al. (2014) applied the CFs from eleven LCIA methods

to mineral resource flows for all market data sets included in the ecoinvent version 3.0 database. The MR taskforce critically reviewed 27 methodological approaches to assess the impacts of mineral resource use (Sonderegger et al., 2020).

The CFs of the ADP method are computed as the ratio between an element's extraction and its ultimate reserves, thereby indicating a relative pressure put on the geological reserves due to human activities. The midpoint CFs of the ReCiPe 2016 method are based on the SOP method (Vieira et al., 2017), and represent the additional amount of ores that will need to be mined in the future as a consequence of present extraction of different elements. Its endpoint CFs come from the Surplus cost potential method (Vieira et al., 2016), measuring the additional costs of metal production in the future linked with the reducing ore quality due to extraction. All of the CFs from the different methods are normalized to kg Fe-eq./kg in order to facilitate the comparison between metals and methods. This normalization is done by dividing all of the CFs by that of iron for the corresponding method. It should be noted that endpoint CFs for metals included in ReCiPe 2016 are equivalent to midpoint ones when normalized to iron equivalents, because the former are calculated from the latter using the same conversion factor calculated for copper (Berger et al., 2020).

The ReCiPe 2016 method has CFs for 75 elementary flows of mineral resources (including uranium), 26 of which are mineral compounds or ores. Parts of the latter 26 flows are no longer included in the ecoinvent database version 3.7.1, since many mineral compounds were converted to pure flows of metal content since version 3.6 (Moreno Ruiz et al., 2019). ADP ultimate reserves has CFs for 75 non-energetic elements, including the 61 metallic elements that are covered by the ADR and LPST methods. Sixteen out of these 61 metals do not yet have corresponding resource flows in ecoinvent version 3.7.1 (i.e., the reason why we considered 45 flows for the study). Missing flows are mostly metals produced as by-products, i.e. germanium, hafnium, indium, iridium, osmium, ruthenium, scandium, and thallium. Other missing metals are bismuth, boron, and heavy rare earth elements, i.e., erbium, holmium, lutetium, thulium, and ytterbium. Of these, boron resource flows are still reported as borax, colemanite and ulexite minerals in ecoinvent version 3.7.1, which is not consistent with the reporting of other metallic elements. CFs for seven of these missing metals are also available in the ReCiPe 2016 method, i.e. bismuth, boron, germanium, hafnium, indium, niobium and thallium. Midpoint CFs are available for all methods, while no endpoint CFs are proposed for the ADP method.

The following method is inspired from the study of Rørbech et al. (2014). The assessment is realized by applying CFs from the selected methods to all nonempty market system process LCI data sets of the ecoinvent database version 3.7.1 (Moreno Ruiz et al., 2020; Wernet et al., 2016) using allocation at

point of substitution (APOS). These include 5,999 sets in total. No end of life scenarios are considered, and therefore the study can be considered as having a cradle-to-gate scope.

Unlike Rørbech et al.'s study, we only considered flows of metal resources in the database that were also covered by the ADR and LPST methods. These include 45 resource flows, categorized as "metals, in ground" (e.g., aluminium, in ground). These 45 flows are also covered by the ADP ultimate reserves method. ReCiPe 2016 does not provide CFs for barium (although one is provided for the mineral barite), rare earth elements (cerium, dysprosium, europium, gadolinium, lanthanum, neodymium, praseodymium, samarium, terbium, and yttrium), and zirconium. Table 6-1 shows all the non-energetic mineral resource flows included in the ecoinvent v3.7.1 database, and the associated CFs for the ADR, LPST, ADP ultimate reserves, and ReCiPe 2016 methods.

Table 6-1. Inventory flows of non-energetic mineral resources present in ecoinvent 3.7.1. and associated characterization factors for selected methods. All CFs are normalized to Fe-eq./kg. As highlighted in the article, ReCiPe 2016 midpoint and endpoint CFs are the same when normalized to Fe-eq./kg. Only inventory flows of resources of metallic elements included in the ecoinvent v3.7.1 database that are also covered by the ADR and LPST methods are included in the application study. The light to dark red scale indicates the relative rank of CFs for each method (lightest = lowest CF).

| Non-energetic mineral resource flows in ecoinvent 3.7.1 database | Form | Flows included in application study | Characterization factors | | | | | | | | | |
|--|---------|-------------------------------------|--------------------------|-------------------|--------------------|--------------------|-----------------------|---------------------------------------|----------------|-------------------|--------------------|--------------------|
| | | | ADR – midpoint | LPST25 – midpoint | LPST100 – midpoint | LPST500 – midpoint | ADP ultimate reserves | ReCiPe 2016 (H) – midpoint & endpoint | ADR – endpoint | LPST25 – endpoint | LPST100 – endpoint | LPST500 – endpoint |
| Aluminium, in ground | Metal | Yes | 2.0E+00 | 1.8E+00 | 1.6E+00 | 1.2E+00 | 3.7E-02 | 2.7E+00 | 5.8E+00 | 5.1E+00 | 4.5E+00 | 3.4E+00 |
| Anhydrite, in ground | Mineral | No | | | | | | | | | | |
| Antimony, in ground | Metal | Yes | 1.3E+01 | 3.6E+00 | 2.8E+00 | 1.4E+00 | 1.4E+06 | 9.2E+00 | 1.3E+02 | 3.7E+01 | 2.9E+01 | 1.4E+01 |
| Arsenic, in ground | Metal | Yes | 8.2E+01 | 5.7E+00 | 3.1E+00 | 1.4E+00 | 3.4E+03 | 2.1E+00 | 6.5E+01 | 4.5E+00 | 2.5E+00 | 1.1E+00 |
| Barium, in ground | Metal | Yes | 6.0E+01 | 5.4E+00 | 3.1E+00 | 1.4E+00 | 2.1E+01 | | 7.2E+00 | 6.6E-01 | 3.8E-01 | 1.7E-01 |
| Basalt, in ground | Mineral | No | | | | | | | | | | |
| Beryllium, in ground | Metal | Yes | 7.2E+00 | 1.9E+00 | 2.5E+00 | 1.4E+00 | 1.1E+02 | 1.2E+03 | 3.6E+03 | 9.3E+02 | 1.2E+03 | 6.7E+02 |
| Borax, in ground | Mineral | No | | | | | | | | | | |
| Cadmium, in ground | Metal | Yes | 1.8E+01 | 4.2E+00 | 2.9E+00 | 1.4E+00 | 5.3E+06 | 5.2E+00 | 7.6E+01 | 1.8E+01 | 1.2E+01 | 5.8E+00 |
| Calcite, in ground | Mineral | No | | | | | | | | | | |
| Calcium, in ground | Metal | No | | | | | 5.2E-01 | | | | | |
| Cerium, in ground | Metal | Yes | 2.7E+01 | 4.8E+00 | 3.0E+00 | 1.4E+00 | 2.9E+01 | | 1.8E+02 | 3.1E+01 | 1.9E+01 | 9.0E+00 |
| Chromium, in ground | Metal | Yes | 2.7E+00 | 2.3E+00 | 1.9E+00 | 1.3E+00 | 1.1E+03 | 1.5E+00 | 7.9E+00 | 6.8E+00 | 5.5E+00 | 3.7E+00 |
| Chrysotile, in ground | Mineral | No | | | | | | 4.9E+00 | | | | |
| Clay, bentonite, in ground | Mineral | No | | | | | | 1.7E-01 | | | | |
| Clay, unspecified, in ground | Mineral | No | | | | | | 1.7E-01 | | | | |
| Cobalt, in ground | Metal | Yes | 3.8E+01 | 5.1E+00 | 3.1E+00 | 1.4E+00 | 3.6E+02 | 1.1E+02 | 1.8E+03 | 2.4E+02 | 1.4E+02 | 6.6E+01 |
| Colemanite, in ground | Mineral | No | | | | | | | | | | |
| Copper, in ground | Metal | Yes | 1.3E+00 | 1.6E+00 | 1.9E+00 | 1.3E+00 | 3.1E+04 | 1.6E+01 | 1.1E+01 | 1.4E+01 | 1.7E+01 | 1.1E+01 |
| Diatomite, in ground | Mineral | No | | | | | | 7.9E-01 | | | | |
| Dolomite, in ground | Mineral | No | | | | | | | | | | |
| Dysprosium, in ground | Metal | Yes | 2.3E+01 | 4.4E+00 | 3.0E+00 | 1.4E+00 | 7.0E+01 | | 7.1E+03 | 1.4E+03 | 9.3E+02 | 4.4E+02 |
| Europium, in ground | Metal | Yes | 6.0E+01 | 5.4E+00 | 3.1E+00 | 1.4E+00 | 4.2E+02 | | 1.9E+04 | 1.7E+03 | 9.7E+02 | 4.4E+02 |
| Feldspar, in ground | Mineral | No | | | | | | 2.5E-01 | | | | |

| Non-energetic mineral resource flows in ecoinvent 3.7.1 database | Form | Flows included in application study | Characterization factors | | | | | | | | | |
|--|---------|-------------------------------------|--------------------------|-------------------|--------------------|--------------------|-----------------------|---------------------------------------|----------------|-------------------|--------------------|--------------------|
| | | | ADR – midpoint | LPST25 – midpoint | LPST100 – midpoint | LPST500 – midpoint | ADP ultimate reserves | ReCiPe 2016 (H) – midpoint & endpoint | ADR – endpoint | LPST25 – endpoint | LPST100 – endpoint | LPST500 – endpoint |
| Fluorine, in ground | Mineral | No | | | | | 1.9E+01 | | | | | |
| Fluorspar, in ground | Mineral | No | | | | | | | | | | |
| Gadolinium, in ground | Metal | Yes | 2.6E+01 | 4.6E+00 | 3.0E+00 | 1.4E+00 | 9.2E+01 | | 1.2E+03 | 2.2E+02 | 1.4E+02 | 6.6E+01 |
| Gallium, in ground | Metal | Yes | 1.4E+03 | 6.0E+00 | 3.2E+00 | 1.4E+00 | 6.1E-01 | 1.4E+03 | 8.5E+05 | 3.7E+03 | 2.0E+03 | 8.7E+02 |
| Gangue, bauxite, in ground | Mineral | No | | | | | | | | | | |
| Gangue, in ground | Mineral | No | | | | | | | | | | |
| Gold, in ground | Metal | Yes | 8.0E-01 | 1.8E+00 | 1.2E+00 | 9.4E-01 | 2.0E+09 | 6.0E+04 | 3.6E+04 | 8.1E+04 | 5.5E+04 | 4.2E+04 |
| Granite, in ground | Mineral | No | | | | | | | | | | |
| Gravel, in ground | Mineral | No | | | | | | | | | | |
| Gypsum, in ground | Mineral | No | | | | | | 4.6E-02 | | | | |
| Iron, in ground | Metal | Yes | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 |
| Kaolinite, in ground | Mineral | No | | | | | | 4.0E-01 | | | | |
| Kieserite, in ground | Mineral | No | | | | | | | | | | |
| Lanthanum, in ground | Metal | Yes | 3.8E+01 | 5.1E+00 | 3.1E+00 | 1.4E+00 | 3.7E+01 | | 2.4E+02 | 3.3E+01 | 1.9E+01 | 8.9E+00 |
| Laterite, in ground | Mineral | No | | | | | | | | | | |
| Lead, in ground | Metal | Yes | 5.6E+00 | 2.3E+00 | 2.3E+00 | 1.3E+00 | 2.7E+04 | 7.9E+00 | 1.6E+01 | 6.7E+00 | 6.8E+00 | 3.8E+00 |
| Lithium, in ground | Metal | Yes | 2.2E+01 | 4.5E+00 | 3.0E+00 | 1.4E+00 | 3.7E+01 | 7.9E+01 | 1.1E+02 | 2.2E+01 | 1.5E+01 | 6.9E+00 |
| Magnesite, in ground | Mineral | No | | | | | | | | | | |
| Magnesium, in ground | Metal | Yes | 2.0E+01 | 5.0E+00 | 2.9E+00 | 1.4E+00 | 2.5E-01 | 1.3E+01 | 1.4E+01 | 3.4E+00 | 2.0E+00 | 9.4E-01 |
| Manganese, in ground | Metal | Yes | 8.3E+00 | 3.8E+00 | 2.6E+00 | 1.4E+00 | 3.6E+01 | 1.3E+00 | 1.5E+01 | 6.6E+00 | 4.6E+00 | 2.4E+00 |
| Mercury, in ground | Metal | Yes | 3.6E+01 | 5.0E+00 | 3.0E+00 | 1.4E+00 | 3.9E+06 | 1.4E+02 | 1.6E+03 | 2.2E+02 | 1.3E+02 | 6.2E+01 |
| Metamorphous rock, graphite containing, in ground | Mineral | No | | | | | | | | | | |
| Molybdenum, in ground | Metal | Yes | 6.3E+00 | 3.3E+00 | 2.4E+00 | 1.3E+00 | 2.5E+05 | 4.7E+02 | 2.9E+02 | 1.5E+02 | 1.1E+02 | 6.2E+01 |
| Neodymium, in ground | Metal | Yes | 2.0E+01 | 4.2E+00 | 2.9E+00 | 1.4E+00 | 3.1E+01 | | 1.3E+03 | 2.8E+02 | 1.9E+02 | 9.2E+01 |
| Nickel, in ground | Metal | Yes | 2.6E+00 | 2.0E+00 | 1.8E+00 | 1.2E+00 | 1.2E+03 | 4.7E+01 | 6.6E+01 | 5.2E+01 | 4.6E+01 | 3.1E+01 |
| Olivine, in ground | Mineral | No | | | | | | | | | | |
| Palladium, in ground | Metal | Yes | 5.4E+00 | 2.5E+00 | 2.3E+00 | 1.3E+00 | 1.4E+09 | 6.9E+04 | 9.6E+04 | 4.5E+04 | 4.1E+04 | 2.4E+04 |
| Perlite, in ground | Metal | No | | | | | | 1.5E-01 | | | | |
| Phosphorus, in ground | Metal | No | | | | | 1.0E+02 | 2.7E+00 | | | | |

| Non-energetic mineral resource flows in ecoinvent 3.7.1 database | Form | Flows included in application study | Characterization factors | | | | | | | | | |
|--|---------|-------------------------------------|--------------------------|-------------------|--------------------|--------------------|-----------------------|---------------------------------------|----------------|-------------------|--------------------|--------------------|
| | | | ADR – midpoint | LPST25 – midpoint | LPST100 – midpoint | LPST500 – midpoint | ADP ultimate reserves | ReCiPe 2016 (H) – midpoint & endpoint | ADR – endpoint | LPST25 – endpoint | LPST100 – endpoint | LPST500 – endpoint |
| Platinum, in ground | Metal | Yes | 3.8E+00 | 2.6E+00 | 2.1E+00 | 1.3E+00 | 1.4E+09 | 1.4E+05 | 1.7E+05 | 1.1E+05 | 9.3E+04 | 5.7E+04 |
| Potassium, in ground | Metal | No | | | | | 1.9E-01 | | | | | |
| Praseodymium, in ground | Metal | Yes | 2.4E+01 | 4.6E+00 | 3.0E+00 | 1.4E+00 | 1.4E+02 | | 2.4E+03 | 4.6E+02 | 3.0E+02 | 1.4E+02 |
| Pumice, in ground | Mineral | No | | | | | | 9.3E-02 | | | | |
| Pyrite, in ground | Mineral | No | | | | | | | | | | |
| Rhenium, in ground | Metal | Yes | 1.5E+01 | 4.0E+00 | 2.9E+00 | 1.4E+00 | 1.5E+09 | 8.5E+03 | 8.2E+04 | 2.2E+04 | 1.5E+04 | 7.5E+03 |
| Rhodium, in ground | Metal | Yes | 6.5E+00 | 2.8E+00 | 2.5E+00 | 1.3E+00 | 4.1E+03 | 1.0E+05 | 5.1E+05 | 2.2E+05 | 1.9E+05 | 1.1E+05 |
| Samarium, in ground | Metal | Yes | 1.4E+01 | 3.5E+00 | 2.8E+00 | 1.4E+00 | 1.1E+02 | | 2.2E+02 | 5.6E+01 | 4.5E+01 | 2.2E+01 |
| Sand, unspecified, in ground | Mineral | No | | | | | | | | | | |
| Selenium, in ground | Metal | Yes | 2.9E+02 | 5.9E+00 | 3.2E+00 | 1.4E+00 | 4.5E+05 | 2.1E+02 | 2.8E+04 | 5.7E+02 | 3.0E+02 | 1.4E+02 |
| Shale, in ground | Mineral | No | | | | | | | | | | |
| Silicon, in ground | Metal | Yes | 1.5E+01 | 3.9E+00 | 2.9E+00 | 1.4E+00 | 1.2E-03 | 6.9E+00 | 4.2E+01 | 1.1E+01 | 7.9E+00 | 3.8E+00 |
| Silver, in ground | Metal | Yes | 3.5E+00 | 1.8E+00 | 2.0E+00 | 1.3E+00 | 1.2E+07 | 2.5E+03 | 2.7E+03 | 1.4E+03 | 1.5E+03 | 1.0E+03 |
| Sodium chloride, in ground | Mineral | No | | | | | | | | | | |
| Sodium nitrate, in ground | Mineral | No | | | | | | | | | | |
| Sodium sulphate, various forms, in ground | Mineral | No | | | | | | | | | | |
| Sodium, in ground | Metal | No | | | | | 2.4E-01 | | | | | |
| Spodumene, in ground | Mineral | No | | | | | | | | | | |
| Steatite, in ground | Mineral | No | | | | | | | | | | |
| Strontium, in ground | Metal | Yes | 2.9E+01 | 4.9E+00 | 3.0E+00 | 1.4E+00 | 2.4E+00 | 1.4E+00 | 3.3E+01 | 5.6E+00 | 3.4E+00 | 1.6E+00 |
| Sulfur, in ground | Mineral | No | | | | | 2.3E+02 | | | | | |
| Sylvite, in ground | Mineral | No | | | | | | | | | | |
| Talc, in ground | Mineral | No | | | | | | 6.1E-01 | | | | |
| Tantalum, in ground | Metal | Yes | 1.7E+01 | 4.0E+00 | 2.9E+00 | 1.4E+00 | 1.8E+03 | 8.5E+02 | 4.0E+03 | 9.7E+02 | 7.0E+02 | 3.3E+02 |
| Tellurium, in ground | Metal | Yes | 2.4E+02 | 5.9E+00 | 3.2E+00 | 1.4E+00 | 2.5E+08 | 3.0E+02 | 4.7E+04 | 1.1E+03 | 6.1E+02 | 2.7E+02 |
| Terbium, in ground | Metal | Yes | 3.0E+01 | 4.8E+00 | 3.0E+00 | 1.4E+00 | 3.8E+02 | | 2.2E+04 | 3.5E+03 | 2.2E+03 | 1.0E+03 |
| Tin, in ground | Metal | Yes | 1.3E+01 | 3.5E+00 | 2.8E+00 | 1.4E+00 | 1.2E+05 | 8.1E+01 | 3.6E+02 | 9.8E+01 | 7.8E+01 | 3.8E+01 |

| Non-energetic mineral resource flows in ecoinvent 3.7.1 database | Form | Flows included in application study | Characterization factors | | | | | | | | | |
|--|---------|-------------------------------------|--------------------------|-------------------|--------------------|--------------------|-----------------------|---------------------------------------|----------------|-------------------|--------------------|--------------------|
| | | | ADR – midpoint | LPST25 – midpoint | LPST100 – midpoint | LPST500 – midpoint | ADP ultimate reserves | ReCiPe 2016 (H) – midpoint & endpoint | ADR – endpoint | LPST25 – endpoint | LPST100 – endpoint | LPST500 – endpoint |
| Titanium, in ground | Metal | Yes | 1.2E+01 | 3.0E+00 | 2.8E+00 | 1.4E+00 | 5.5E-01 | 1.4E+01 | 1.7E+02 | 4.5E+01 | 4.2E+01 | 2.1E+01 |
| Tungsten, in ground | Metal | Yes | 2.7E+01 | 4.7E+00 | 3.0E+00 | 1.4E+00 | 3.0E+04 | 1.3E+02 | 1.3E+03 | 2.2E+02 | 1.4E+02 | 6.7E+01 |
| Ulexite, in ground | Mineral | No | | | | | | | | | | |
| Vanadium, in ground | Metal | Yes | 2.0E+01 | 4.8E+00 | 2.9E+00 | 1.4E+00 | 9.5E+00 | 6.4E+01 | 6.7E+02 | 1.6E+02 | 9.9E+01 | 4.7E+01 |
| Vermiculite, in ground | Mineral | No | | | | | | | | | | |
| Yttrium, in ground | Metal | Yes | 2.7E+01 | 4.9E+00 | 3.0E+00 | 1.4E+00 | 1.6E+01 | | 1.0E+03 | 1.8E+02 | 1.1E+02 | 5.3E+01 |
| Zinc, in ground | Metal | Yes | 6.2E+00 | 2.7E+00 | 2.4E+00 | 1.3E+00 | 4.0E+03 | 2.5E+00 | 1.8E+01 | 7.9E+00 | 7.1E+00 | 4.0E+00 |
| Zirconium, in ground | Metal | Yes | 1.0E+01 | 3.2E+00 | 2.7E+00 | 1.4E+00 | 3.8E+01 | | 1.5E+01 | 4.8E+00 | 4.0E+00 | 2.1E+00 |

To facilitate the comparison's intelligibility and indicate general trends that could be expected from using the ADR and LPST methods in LCA studies, the LCI data sets were subdivided per economic activity sectors established in the International Standard Industrial Classification of All Economic Activities (ISIC) (United Nations, 2008). The ecoinvent database v3.7.1 (Wernet et al., 2016) includes 5999 non-empty market data sets. Of these, section A (Agriculture, forestry and fishing) contains 404 market data sets; section B (Mining and quarrying), 202 market data sets; Section C (Manufacturing), 2800 market data sets; Section D (Electricity, gas, steam and air conditioning supply), 636 market data sets, Section E (Water supply; sewerage, waste management & remediation activities), 1210 market data sets; Section F (Construction), 282 market data sets; Section H (Transportation and storage), 203 market data sets; and Other sections, 262 market data sets. In order to support the analysis of the contribution of the different sections of economic activity to the inventory totals (section 6.3.2), the total mass for 45 studied metal flows per section of economic activity are shown in Figure 6-1.

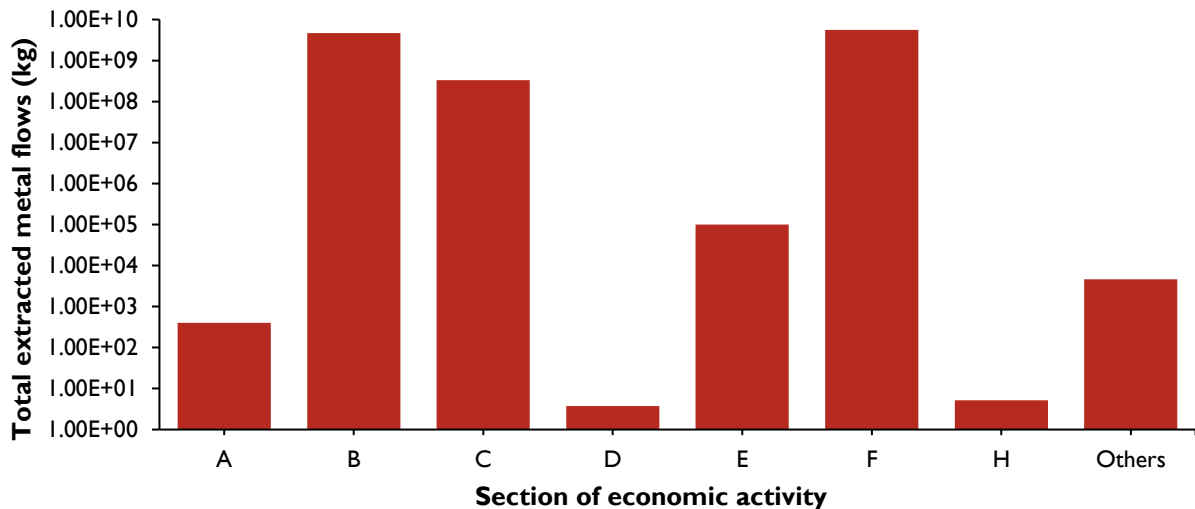


Figure 6-1. Total mass of extracted metal flows in the ecoinvent database per section of economic activity.

The total mass is the sum for the 45 metals considered in the application study, as shown in Table 6-1.

Section G is included in Others.

6.3 Results and analysis

In this section, we first analyze impact assessment results for defined sections of economic activity using midpoint methods (section 6.3.1). We then compare total impacts between midpoint and endpoint assessments (section 6.3.2). Finally, we compare the absolute impact assessments for all 5999 data sets grouped by section of economic activity across the four studied LCIA methods, i.e., ADR, LPST, ADP and ReCiPe 2016 (section 6.3.3).

Results are shown in Figure 6-2, Figure 6-3, Table 6-2 and Table 6-3. Figure 6-2 shows the relative contribution of metals to inventory results and midpoint impacts for selected LCIA methods divided per section of economic activity. Figure 6-3 shows relative contribution of metals to midpoint and endpoint impacts for selected LCIA methods applied to all market data sets, i.e. the sum of impacts for all economic sections. The absolute and relative contributions of different metals to the inventory totals and impact assessment results underlying Figure 6-3 are shown in Table 6-2 (midpoint results) and Table 6-3 (endpoint results), displayed at the bottom of section 6.3.2.

6.3.1 Comparison between inventory and midpoint impact assessment results

Figure 6-2 shows that impact results for the LPST25, 100 and 500 methods are increasingly similar to the inventory shares of metals. Iron largely dominates resource extraction in the inventories for all studied sectors with between 76% (section C: Manufacturing) and 98% (section B: Mining and quarrying) of their shares. Its relative impacts are negligible for ADP ultimate reserves, since its annual production is very small in comparison to its geological reserves: iron represents about 5% of the upper crust's composition, and its CF is amongst the lowest for that method, with $6.92\text{E-}07$ kg Sb eq. (van Oers et al., 2019). They are increasingly important for ADR, ReCiPe, LPST25, LPST100 and LPST500. Indeed, while the CF of iron is the second lowest for these latter methods, their CFs spread over less orders of magnitudes than ADP's as they depend on the dissipation of metals after extraction, for which much less variations than production and geological reserves are observed (cf. Chapter 5). Hence, the high shares of iron in the inventory are still reflected in impact results when using these methods.

Of metals with smaller shares of extraction in the inventories, precious metals (silver, gold, palladium, and platinum), that have small crustal concentrations, recurrently come up as the main contributors to the ADP impact assessment results. Indeed, these metals all have very low crustal contents underlying the estimation of ultimate reserves used in the computation of CFs, with 0.0000053% for silver at most (van Oers et al., 2019). Notably, gold consistently comes up as one of the main contributor to ADP's results despite its small share in the inventories, with around 0.0004% of total extraction by weight. Its CF is $2.0\text{E}+09$ times that of iron (Table 6-1). Gold's share of impacts for the ADP method range from 15% for section A (Agriculture, forestry and fishing) to 70% for section C (Mining). Palladium and platinum show up as important contributors for section C, with 11% and 16%, respectively, and section H (Transportation and storage), with 10% and 15%, respectively. Finally, silver comes up as a main contributor for the other sections, with 0.009% of the inventory totals, and 29% of ADP's total impacts. The results for ADP also show that copper and tellurium repeatedly come up as important contributors to the impacts of depletion across most sectors of economic activity. Indeed,

their CFs are amongst the highest for the ADP ultimate reserve methods, given relatively high extraction rates in comparison to ultimate reserves: the CF for copper ranks 33rd highest, and tellurium, 41st highest amongst those for the 45 studied metals. Hence, tellurium comes up as an important contributor for all sections except A and C, with between 11% and 41% of ADP's category totals, despite consistently low shares of the inventory totals for the categories (0.0005% at most). In contrast, copper has a relatively high CF in comparison to other widely extracted metals (e.g. barium and manganese's CFs rank 10th and 13th, respectively, while their inventory shares are overall similar to those of copper). This explains its important contribution to category totals for ADP for sections A: Agriculture, forestry and fishing (18%), B: Mining and quarrying (15%), D: Electricity, gas, steam and air conditioning supply (16%), E: Electricity, gas, steam and air conditioning supply (12%), and F: Construction (16%), while its shares of inventory totals range from 0.94% to 1.5% across these sections.

Similarly to ADP, precious metals (gold, palladium, platinum, and silver) reveal to be important contributors to the ReCiPe 2016 impacts for sections with the highest shares of these precious metals in the inventory totals (sections C, H, and Other sections), suggesting that a lot of additional ores will need to be mined to replace depleted ones given their low concentrations at mining sites (i.e., high surplus ore potentials). Indeed, CFs for these metals rank amongst the highest in ReCiPe 2016. For instance, the CFs of gold and platinum are 60 258 and 141 681 times that of iron, and rank 30th and 33rd highest out of 33 CFs of the ReCiPe 2016 method considered for this study, respectively (Table 6-1). In addition, the share of impacts for copper with the ReCiPe 2016 method shows similar patterns as those for the ADP ultimate reserves method: it represents 12% of impacts for sections A, 14% for section D, 9.6% for section E, and 9.0% for section F. While copper's CF for the ReCiPe 2016 method is not as high ranked as for ADP (14th out of 33 CFs considered for the former method), the method's CFs range over much less orders of magnitude as those of ADP, and hence its category totals are less affected by small amounts of very scarce metals. In contrast to ADP and ReCiPe 2016, precious metals and copper do not show up in the top five contributors to total impact scores for the ADR and LPST methods, because their midpoint CFs consistently range amongst the smallest (cf. Table 6-1 and Chapter 5).

Nickel also comes up as an important contributor to ReCiPe 2016 relative impacts for the construction sector (F) as well as the transportation and storage sectors (H), with 45% and 11% of their total impacts, respectively. The ADP, ADR and LPST results are also sensible to nickel extraction, albeit much less than ReCiPe 2016, as observable for these latter two sections of economic activity. It comes up as the third highest contributor to the ADR and LPST impact assessment for the construction sector, with around 3-5% of their total impacts. The ADR and LPST methods show that barium is often part of the main contributors for the total impacts due to dissipation, in contrast to ADP's results (as noted earlier, no

CF is available for barium in ReCiPe 2016). Barium is mostly used for gas and oil well drilling under its mineral form of barites, likely explaining its large use in energy-intensive sectors, and also explaining its highly dissipative profile best distinguished with the ADR method. Zinc also shows up as a main contributor for the ADP and LPST methods for section C (manufacturing) and the other sections. This is explained by higher CFs for zinc in comparison to other widely extracted metals with similar shares of the inventory totals, and especially by the larger share of zinc in the inventory totals for these two sections. As an indication, barium and zinc represent about 1% and 4.5% of the studied inventory flows by weight for the manufacturing section, while they respectively account for 18% and 12% of the total impacts for the midpoint ADR method. In comparison to zinc, aluminium flows represent 4.7% of the inventory totals for section C (just over that of zinc), but its midpoint CFs for the ADR and LPST100 methods are 67% and 35% lower than corresponding CFs for zinc, respectively. This explains why aluminium does not show up in top five contributions for this section, whereas zinc does.

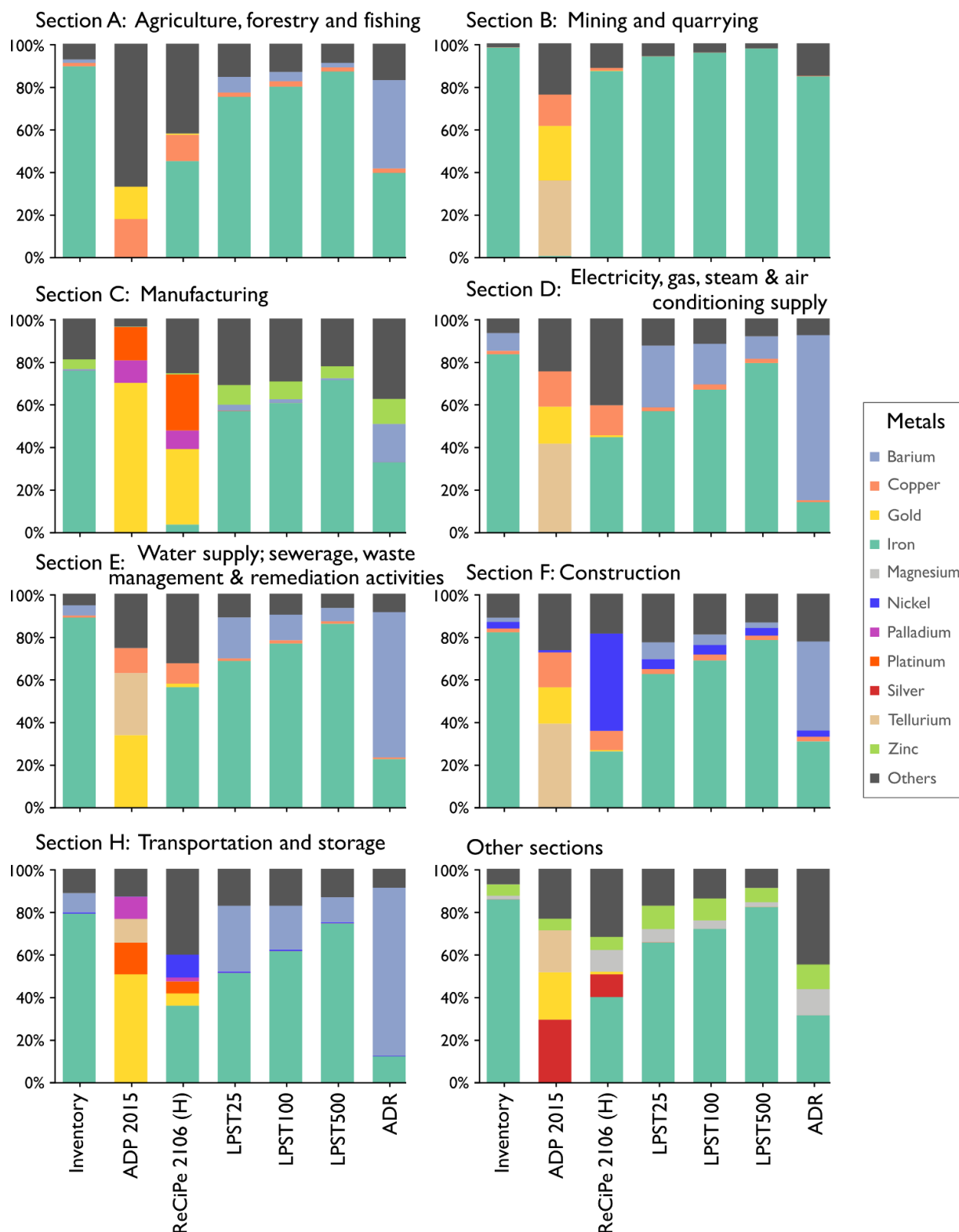


Figure 6-2. Contribution of metals to total impacts for four distinct midpoint LCIA methods. Graphs present results per sector of activity established in the ISIC. The inventory column presents the relative mass of extracted resources in the compiled LCI data sets. Metals that are attributed over 10% of the total impacts for at least one impact method are shown individually for the corresponding sector of activity; others are grouped altogether.

Figure 6-3 shows inventory and midpoint impact results for LCIA methods applied to all market data sets, i.e. the sum of impacts for all economic sections. The five metals contributing most to inventory totals are iron (89%), chromium (2.6%), nickel (1.8%), aluminium (1.8%), and manganese (1.4%). Copper, barium and zinc follow-up closely, with 1.2%, 1.1% and 0.6% of the contribution to resource flows in the inventory, respectively. Out of these widely produced metals, only copper appears in the top five metals in the midpoint impact assessment with ADP, with about 3% of the total impacts. Contrastingly, iron represents a large share of impacts for the other midpoint assessment results, albeit being consistently lower than the inventory's share. Nickel also shows as one of the top five metals across the ReCiPe 2016 and LPST100 midpoint impact scores (30% and 3% of their respective category totals). Barium, chromium and manganese repeatedly show up in top results for ADR, with 33%, 3% and 6% of its category total, respectively. Barium's share of the LPST100's category total is ten times lower than ADR's (3%); chromium's share is similar (4%), and manganese's share is half that of ADR (3%). This puts forward potentially substantial differences between impact assessment results when using the ADR or the LPST methods, since the CFs of the ADR method are more sensitive to highly dissipative metal profiles like that of barium.

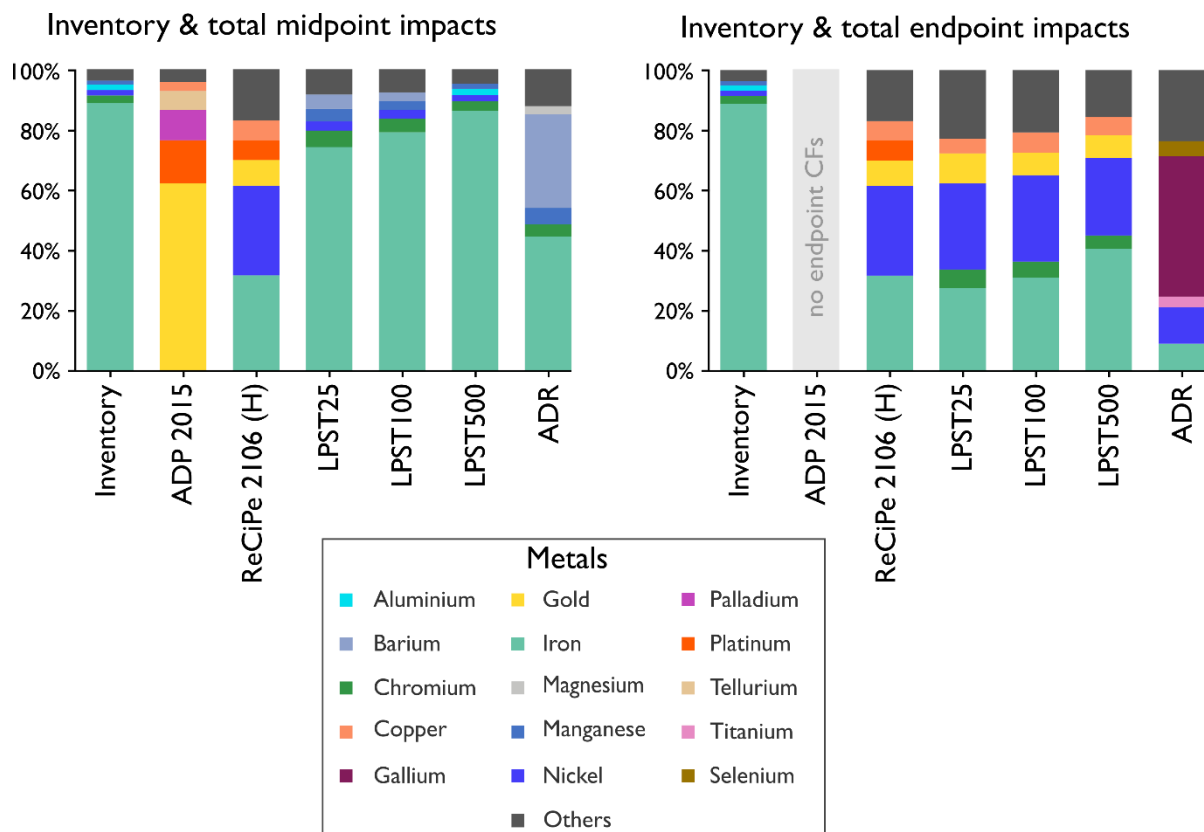


Figure 6-3. Inventory contributions and total midpoint and endpoint impact scores for selected LCIA methods applied to 5 999 market data sets from the ecoinvent database. Metals representing the top five contributions for inventories and for each LCIA method are shown in their respective columns; others are grouped altogether.

6.3.2 Evolution between midpoint and endpoint impact assessment

Based on Figure 6-3, we here investigate how impacts evolve from the midpoint to the endpoint assessment, focusing on impact scores for the ADR and LPST methods, given that midpoint and endpoint CFs of the ReCiPe 2016 method are the same amongst the studied metals when normalized to iron equivalents, and that ADP only provides midpoint CFs. Indeed, the endpoint CFs for the ADR and LPST100 methods, computed with their price index (cf. Chapter 5), allow differentiating between metals, which is not the case for the endpoint CFs of the ReCiPe 2016 method. Indeed, the latter rely on the same factor to convert surplus ore potentials (midpoint) into surplus cost potentials (endpoint) (Berger et al., 2020). Hence, the ADR and LPST's endpoint CFs provide more metal-specific information in their endpoint computation, improving the differentiation between mineral resources in comparison to ReCiPe 2016's endpoint CFs that do not (Figure 6-3). We only discuss numerical results for LPST100 to avoid redundancy. It should be noted that these impact results are driven by a few data sets with much larger than average inventory flows (cf. Figure 6-4).

The impacts of the dissipation of lower priced metals become relatively smaller in the endpoint in comparison to the midpoint assessment because of the way endpoint CFs are computed for the LPST and ADR methods. For instance, while barium's share of impacts is most apparent in the midpoint assessment for these methods, they drop below 1% of their category totals in the endpoint because of its low price. Indeed, barium is the cheapest of all studied metals and its price index is of 0.12. The share of impacts attributed to iron flows decrease substantially in the endpoint assessment, although they remain notable with around one third of the total impacts for LPST100, and 9% for ADR. Conversely, endpoint impacts due to the dissipation of higher priced metals increase importantly. For instance, gold and nickel see their shares skyrocket in the endpoint scores for the LPST100 method. Notably, gold's share of total impacts for the latter method ramped up from 0.0004% to 8% between the midpoint and endpoint assessments due to its very high price index of 44 621. Copper and nickel, with smaller price indexes of 8.74 and 25.2, respectively, see their respective shares of the LPST100 category totals increase importantly between the midpoint and endpoint assessments. This increase is from 2% to 7% for copper, and from 3% to 29% for nickel.

Midpoint and endpoint assessments using the ADR method follows similar trends as LPST100; however, metals that are lost rapidly after extraction see their relative shares of impact grow more importantly than for LPSTs in the endpoint assessment. This is particularly the case for by-product metals that are not often produced along with carrier metals during primary production, and that are costly to produce, hence having a high market price. For instance, gallium and selenium's respective shares of inventory totals are of 0.00054% and 0.0017%; those of midpoint impacts, of 0.36% and

0.24%; and those of endpoint impacts, of 47% and 5.0%. Indeed, their relatively high midpoint CFs are further boosted by their relatively high prices: gallium's price index is of 614, and that of selenium, of 95.9. Moreover, other metals with relatively high shares of inventory totals, average midpoint ADRs, and higher prices than iron, become more prominent in endpoint results. For instance, titanium's price index is of 15.1; it represents 0.13% of inventory flows, and its share of the category totals for the ADR method increases from 0.74% for the midpoint to 2.3% for the endpoint assessment. This is explained by a greater price index for titanium in comparison to other metals contributing most to inventory totals. Indeed, its endpoint CF increased by a factor of 15 in comparison to its midpoint CF, while that of the ten other metals with the greatest shares of inventory totals aside from zinc (the latter is also part of the top five impact contributors for the endpoint ADR assessment) changed by a factor of 2.7 on average.

Finally, it can be observed that four out of five top contributions (copper, gold, iron and nickel) are common to the endpoint assessment of ReCiPe 2016 and LPST100 methods, with similar relative contributions to their respective impact scores (Figure 6-3). This convergence can be explained by the similarities between the surplus amount of ores required to produce scarcer metals in the future, its associated cost, and the higher economic value of these same metals. Indeed, production costs generally represent approximately 75% of a metal's market price (Huppertz et al., 2019). We showed in Chapter 5 that the endpoint CFs of the LPST method were most influenced by the price-index of metals.

Table 6-2. Absolute total midpoint impact assessment results per metal and relative contribution to category totals (%). Top-five contributions (as shown in Figure 6-3) are highlighted in dark orange; the following 6th to 10th contributions are highlighted in light orange.

| Inventory flows | Inventory (kg) | % | Midpoint totals (kg Fe-eq.) | | | | | | | | | | | |
|-------------------------|----------------|----------|-----------------------------|------|-------------|------|----------|------|----------|------|----------|------|----------|------|
| | | | ADP2015 | % | RECIPE 2016 | % | LPST25 | % | LPST100 | % | LPST500 | % | ADR | % |
| Iron, in ground | 9.38E+09 | 88.8% | 9.38E+09 | 0.0% | 9.38E+09 | 32% | 9.38E+09 | 74% | 9.38E+09 | 79% | 9.38E+09 | 86% | 9.38E+09 | 44% |
| Chromium, in ground | 2.74E+08 | 2.6% | 3.13E+11 | 0.2% | 4.20E+08 | 1.4% | 6.42E+08 | 5.1% | 5.13E+08 | 4.3% | 3.43E+08 | 3.1% | 7.44E+08 | 3.5% |
| Nickel, in ground | 1.89E+08 | 1.8% | 2.22E+11 | 0.2% | 8.82E+09 | 30% | 3.86E+08 | 3.1% | 3.44E+08 | 2.9% | 2.36E+08 | 2.2% | 4.97E+08 | 2.3% |
| Aluminium, in ground | 1.87E+08 | 1.8% | 6.87E+06 | 0.0% | 5.10E+08 | 1.7% | 3.33E+08 | 2.6% | 2.92E+08 | 2.5% | 2.24E+08 | 2.1% | 3.80E+08 | 1.8% |
| Manganese, in ground | 1.43E+08 | 1.4% | 5.16E+09 | 0.0% | 1.90E+08 | 0.6% | 5.36E+08 | 4.2% | 3.73E+08 | 3.1% | 1.94E+08 | 1.8% | 1.19E+09 | 5.6% |
| Copper, in ground | 1.23E+08 | 1.2% | 3.79E+12 | 2.9% | 1.99E+09 | 6.7% | 1.93E+08 | 1.5% | 2.33E+08 | 2.0% | 1.58E+08 | 1.4% | 1.58E+08 | 0.7% |
| Barium, in ground | 1.17E+08 | 1.1% | 2.43E+09 | 0.0% | 0.00E+00 | 0.0% | 6.36E+08 | 5.0% | 3.63E+08 | 3.1% | 1.65E+08 | 1.5% | 6.98E+09 | 33% |
| Zinc, in ground | 6.41E+07 | 0.61% | 2.56E+11 | 0.2% | 1.58E+08 | 0.5% | 1.73E+08 | 1.4% | 1.55E+08 | 1.3% | 8.61E+07 | 0.8% | 3.98E+08 | 1.9% |
| Magnesium, in ground | 2.89E+07 | 0.27% | 7.30E+06 | 0.0% | 3.69E+08 | 1.2% | 1.44E+08 | 1.1% | 8.52E+07 | 0.7% | 4.03E+07 | 0.4% | 5.93E+08 | 2.8% |
| Silicon, in ground | 2.46E+07 | 0.23% | 2.92E+04 | 0.0% | 1.70E+08 | 0.6% | 9.51E+07 | 0.8% | 7.06E+07 | 0.6% | 3.41E+07 | 0.3% | 3.78E+08 | 1.8% |
| Lead, in ground | 1.39E+07 | 0.13% | 3.75E+11 | 0.3% | 1.10E+08 | 0.4% | 3.24E+07 | 0.3% | 3.26E+07 | 0.3% | 1.86E+07 | 0.2% | 7.85E+07 | 0.4% |
| Titanium, in ground | 1.36E+07 | 0.13% | 7.42E+06 | 0.0% | 1.93E+08 | 0.6% | 4.09E+07 | 0.3% | 3.74E+07 | 0.3% | 1.87E+07 | 0.2% | 1.57E+08 | 0.7% |
| Molybdenum, in ground | 2.39E+06 | 0.023% | 5.98E+11 | 0.5% | 1.13E+09 | 3.8% | 7.78E+06 | 0.1% | 5.84E+06 | 0.0% | 3.21E+06 | 0.0% | 1.52E+07 | 0.1% |
| Cerium, in ground | 2.38E+06 | 0.023% | 6.80E+07 | 0.0% | 0.00E+00 | 0.0% | 1.15E+07 | 0.1% | 7.16E+06 | 0.1% | 3.33E+06 | 0.0% | 6.54E+07 | 0.3% |
| Zirconium, in ground | 2.19E+06 | 0.021% | 8.31E+07 | 0.0% | 0.00E+00 | 0.0% | 6.97E+06 | 0.1% | 5.91E+06 | 0.0% | 3.00E+06 | 0.0% | 2.20E+07 | 0.1% |
| Lanthanum, in ground | 1.69E+06 | 0.016% | 6.33E+07 | 0.0% | 0.00E+00 | 0.0% | 8.68E+06 | 0.1% | 5.17E+06 | 0.0% | 2.37E+06 | 0.0% | 6.38E+07 | 0.3% |
| Tin, in ground | 9.01E+05 | 0.0085% | 1.06E+11 | 0.1% | 7.32E+07 | 0.2% | 3.17E+06 | 0.0% | 2.53E+06 | 0.0% | 1.24E+06 | 0.0% | 1.16E+07 | 0.1% |
| Neodymium, in ground | 7.37E+05 | 0.0070% | 2.30E+07 | 0.0% | 0.00E+00 | 0.0% | 3.11E+06 | 0.0% | 2.16E+06 | 0.0% | 1.03E+06 | 0.0% | 1.45E+07 | 0.1% |
| Cobalt, in ground | 4.97E+05 | 0.0047% | 1.80E+08 | 0.0% | 5.28E+07 | 0.2% | 2.55E+06 | 0.0% | 1.52E+06 | 0.0% | 6.97E+05 | 0.0% | 1.89E+07 | 0.1% |
| Silver, in ground | 2.68E+05 | 0.0025% | 3.35E+12 | 2.5% | 6.63E+08 | 2.2% | 4.92E+05 | 0.0% | 5.26E+05 | 0.0% | 3.45E+05 | 0.0% | 9.33E+05 | 0.0% |
| Praseodymium, in ground | 2.39E+05 | 0.0023% | 3.34E+07 | 0.0% | 0.00E+00 | 0.0% | 1.09E+06 | 0.0% | 7.11E+05 | 0.0% | 3.33E+05 | 0.0% | 5.67E+06 | 0.0% |
| Selenium, in ground | 1.85E+05 | 0.0017% | 8.34E+10 | 0.1% | 3.97E+07 | 0.1% | 1.10E+06 | 0.0% | 5.86E+05 | 0.0% | 2.61E+05 | 0.0% | 5.34E+07 | 0.3% |
| Samarium, in ground | 6.41E+04 | 0.00061% | 7.12E+06 | 0.0% | 0.00E+00 | 0.0% | 2.25E+05 | 0.0% | 1.82E+05 | 0.0% | 8.86E+04 | 0.0% | 9.06E+05 | 0.0% |
| Gallium, in ground | 5.68E+04 | 0.00054% | 3.45E+04 | 0.0% | 7.69E+07 | 0.3% | 3.42E+05 | 0.0% | 1.81E+05 | 0.0% | 8.02E+04 | 0.0% | 7.86E+07 | 0.4% |
| Gold, in ground | 4.16E+04 | 0.00039% | 8.23E+13 | 62% | 2.50E+09 | 8.5% | 7.59E+04 | 0.0% | 5.13E+04 | 0.0% | 3.92E+04 | 0.0% | 3.33E+04 | 0.0% |

| | | | Midpoint totals (kg Fe-eq.) | | | | | | | | | | | |
|-----------------------|----------------|-----------|-----------------------------|------|-------------|------|----------|------|----------|------|----------|------|----------|------|
| Inventory flows | Inventory (kg) | % | ADP2015 | % | RECIPE 2016 | % | LPST25 | % | LPST100 | % | LPST500 | % | ADR | % |
| Tellurium, in ground | 3.40E+04 | 0.00032% | 8.37E+12 | 6.3% | 1.03E+07 | 0.0% | 2.01E+05 | 0.0% | 1.08E+05 | 0.0% | 4.80E+04 | 0.0% | 8.27E+06 | 0.0% |
| Gadolinium, in ground | 3.05E+04 | 0.00029% | 2.82E+06 | 0.0% | 0.00E+00 | 0.0% | 1.41E+05 | 0.0% | 9.14E+04 | 0.0% | 4.26E+04 | 0.0% | 7.97E+05 | 0.0% |
| Yttrium, in ground | 2.82E+04 | 0.00027% | 4.53E+05 | 0.0% | 0.00E+00 | 0.0% | 1.38E+05 | 0.0% | 8.48E+04 | 0.0% | 3.95E+04 | 0.0% | 7.59E+05 | 0.0% |
| Strontium, in ground | 1.71E+04 | 0.00016% | 4.10E+04 | 0.0% | 2.42E+04 | 0.0% | 8.45E+04 | 0.0% | 5.15E+04 | 0.0% | 2.39E+04 | 0.0% | 4.92E+05 | 0.0% |
| Platinum, in ground | 1.35E+04 | 0.00013% | 1.90E+13 | 14% | 1.92E+09 | 6.5% | 3.49E+04 | 0.0% | 2.86E+04 | 0.0% | 1.76E+04 | 0.0% | 5.09E+04 | 0.0% |
| Tungsten, in ground | 1.29E+04 | 0.00012% | 3.92E+08 | 0.0% | 1.62E+06 | 0.0% | 6.02E+04 | 0.0% | 3.88E+04 | 0.0% | 1.80E+04 | 0.0% | 3.46E+05 | 0.0% |
| Europium, in ground | 1.20E+04 | 0.00011% | 5.04E+06 | 0.0% | 0.00E+00 | 0.0% | 6.50E+04 | 0.0% | 3.72E+04 | 0.0% | 1.69E+04 | 0.0% | 7.16E+05 | 0.0% |
| Tantalum, in ground | 1.06E+04 | 0.00010% | 1.93E+07 | 0.0% | 9.06E+06 | 0.0% | 4.25E+04 | 0.0% | 3.06E+04 | 0.0% | 1.47E+04 | 0.0% | 1.77E+05 | 0.0% |
| Arsenic, in ground | 9.79E+03 | 0.00009% | 3.34E+07 | 0.0% | 2.07E+04 | 0.0% | 5.59E+04 | 0.0% | 3.06E+04 | 0.0% | 1.38E+04 | 0.0% | 7.99E+05 | 0.0% |
| Palladium, in ground | 9.49E+03 | 0.00009% | 1.32E+13 | 10% | 6.56E+08 | 2.2% | 2.39E+04 | 0.0% | 2.20E+04 | 0.0% | 1.26E+04 | 0.0% | 5.11E+04 | 0.0% |
| Dysprosium, in ground | 7.70E+03 | 0.00007% | 5.40E+05 | 0.0% | 0.00E+00 | 0.0% | 3.41E+04 | 0.0% | 2.29E+04 | 0.0% | 1.07E+04 | 0.0% | 1.74E+05 | 0.0% |
| Cadmium, in ground | 7.46E+03 | 0.00007% | 3.92E+10 | 0.0% | 3.86E+04 | 0.0% | 3.13E+04 | 0.0% | 2.17E+04 | 0.0% | 1.04E+04 | 0.0% | 1.36E+05 | 0.0% |
| Terbium, in ground | 4.62E+03 | 0.00004% | 1.78E+06 | 0.0% | 0.00E+00 | 0.0% | 2.24E+04 | 0.0% | 1.40E+04 | 0.0% | 6.46E+03 | 0.0% | 1.40E+05 | 0.0% |
| Lithium, in ground | 2.48E+03 | 0.00002% | 9.23E+04 | 0.0% | 1.95E+05 | 0.0% | 1.12E+04 | 0.0% | 7.35E+03 | 0.0% | 3.46E+03 | 0.0% | 5.41E+04 | 0.0% |
| Rhodium, in ground | 1.78E+03 | 0.00002% | 7.28E+06 | 0.0% | 1.82E+08 | 0.6% | 4.97E+03 | 0.0% | 4.36E+03 | 0.0% | 2.39E+03 | 0.0% | 1.15E+04 | 0.0% |
| Beryllium, in ground | 5.12E+02 | 0.000005% | 5.86E+04 | 0.0% | 6.34E+05 | 0.0% | 9.59E+02 | 0.0% | 1.28E+03 | 0.0% | 6.93E+02 | 0.0% | 3.68E+03 | 0.0% |
| Antimony, in ground | 3.50E+02 | 0.000003% | 5.06E+08 | 0.0% | 3.24E+03 | 0.0% | 1.26E+03 | 0.0% | 9.81E+02 | 0.0% | 4.83E+02 | 0.0% | 4.46E+03 | 0.0% |
| Vanadium, in ground | 2.90E+02 | 0.000003% | 2.76E+03 | 0.0% | 1.86E+04 | 0.0% | 1.40E+03 | 0.0% | 8.52E+02 | 0.0% | 4.04E+02 | 0.0% | 5.78E+03 | 0.0% |
| Rhenium, in ground | 2.44E+02 | 0.000002% | 3.69E+11 | 0.3% | 2.08E+06 | 0.0% | 9.82E+02 | 0.0% | 6.99E+02 | 0.0% | 3.38E+02 | 0.0% | 3.70E+03 | 0.0% |
| Mercury, in ground | 8.70E+01 | 0.000001% | 3.40E+08 | 0.0% | 1.26E+04 | 0.0% | 4.39E+02 | 0.0% | 2.65E+02 | 0.0% | 1.22E+02 | 0.0% | 3.15E+03 | 0.0% |

Table 6-3. Absolute total endpoint impact assessment results per metal and relative contribution to category totals (%). Top-five contributions (as shown in Figure 6-3) are highlighted in dark orange; the following 6th to 10th contributions are highlighted in light orange.

| Inventory flows | Inventory (kg) | % | Endpoint totals (kg Fe-eq.) | | | | | | | | | |
|-------------------------|----------------|----------|-----------------------------|------|----------|-------|----------|------|----------|------|----------|------|
| | | | ReCiPe 2016 | % | LPST25 | % | LPST100 | % | LPST500 | % | ADR | % |
| Iron, in ground | 9.38E+09 | 88.8% | 9.38E+09 | 32% | 9.38E+09 | 28% | 9.38E+09 | 31% | 9.38E+09 | 41% | 9.38E+09 | 9.3% |
| Chromium, in ground | 2.74E+08 | 2.6% | 4.21E+08 | 1.4% | 1.87E+09 | 5.5% | 1.49E+09 | 5.0% | 9.99E+08 | 4.3% | 2.17E+09 | 2.2% |
| Nickel, in ground | 1.89E+08 | 1.8% | 8.82E+09 | 30% | 9.73E+09 | 29% | 8.65E+09 | 29% | 5.93E+09 | 26% | 1.25E+10 | 12% |
| Aluminium, in ground | 1.87E+08 | 1.8% | 5.11E+08 | 1.7% | 9.50E+08 | 2.8% | 8.33E+08 | 2.8% | 6.40E+08 | 2.8% | 1.08E+09 | 1.1% |
| Manganese, in ground | 1.43E+08 | 1.4% | 1.90E+08 | 0.6% | 9.36E+08 | 2.8% | 6.51E+08 | 2.2% | 3.39E+08 | 1.5% | 2.08E+09 | 2.1% |
| Copper, in ground | 1.23E+08 | 1.2% | 1.99E+09 | 6.7% | 1.69E+09 | 5.0% | 2.04E+09 | 6.8% | 1.38E+09 | 6.0% | 1.38E+09 | 1.4% |
| Barium, in ground | 1.17E+08 | 1.1% | 0.00E+00 | 0.0% | 7.74E+07 | 0.2% | 4.42E+07 | 0.1% | 2.00E+07 | 0.1% | 8.49E+08 | 0.8% |
| Zinc, in ground | 6.41E+07 | 0.61% | 1.59E+08 | 0.5% | 5.09E+08 | 1.5% | 4.56E+08 | 1.5% | 2.54E+08 | 1.1% | 1.17E+09 | 1.2% |
| Magnesium, in ground | 2.89E+07 | 0.27% | 3.70E+08 | 1.2% | 9.74E+07 | 0.3% | 5.76E+07 | 0.2% | 2.72E+07 | 0.1% | 4.01E+08 | 0.4% |
| Silicon, in ground | 2.46E+07 | 0.23% | 1.71E+08 | 0.6% | 2.62E+08 | 0.8% | 1.94E+08 | 0.6% | 9.39E+07 | 0.4% | 1.04E+09 | 1.0% |
| Lead, in ground | 1.39E+07 | 0.13% | 1.10E+08 | 0.4% | 9.32E+07 | 0.3% | 9.38E+07 | 0.3% | 5.34E+07 | 0.2% | 2.25E+08 | 0.2% |
| Titanium, in ground | 1.36E+07 | 0.13% | 1.92E+08 | 0.6% | 6.16E+08 | 1.8% | 5.64E+08 | 1.9% | 2.81E+08 | 1.2% | 2.36E+09 | 2.3% |
| Molybdenum, in ground | 2.39E+06 | 0.023% | 1.13E+09 | 3.8% | 3.60E+08 | 1.1% | 2.70E+08 | 0.9% | 1.49E+08 | 0.6% | 7.02E+08 | 0.7% |
| Cerium, in ground | 2.38E+06 | 0.023% | 0.00E+00 | 0.0% | 7.41E+07 | 0.2% | 4.62E+07 | 0.2% | 2.15E+07 | 0.1% | 4.22E+08 | 0.4% |
| Zirconium, in ground | 2.19E+06 | 0.021% | 0.00E+00 | 0.0% | 1.05E+07 | 0.0% | 8.86E+06 | 0.0% | 4.50E+06 | 0.0% | 3.31E+07 | 0.0% |
| Lanthanum, in ground | 1.69E+06 | 0.016% | 0.00E+00 | 0.0% | 5.52E+07 | 0.2% | 3.29E+07 | 0.1% | 1.51E+07 | 0.1% | 4.06E+08 | 0.4% |
| Tin, in ground | 9.01E+05 | 0.0085% | 7.31E+07 | 0.2% | 8.82E+07 | 0.3% | 7.03E+07 | 0.2% | 3.46E+07 | 0.1% | 3.23E+08 | 0.3% |
| Neodymium, in ground | 7.37E+05 | 0.0070% | 0.00E+00 | 0.0% | 2.06E+08 | 0.6% | 1.43E+08 | 0.5% | 6.78E+07 | 0.3% | 9.58E+08 | 1.0% |
| Cobalt, in ground | 4.97E+05 | 0.0047% | 5.29E+07 | 0.2% | 1.20E+08 | 0.4% | 7.17E+07 | 0.2% | 3.29E+07 | 0.1% | 8.91E+08 | 0.9% |
| Silver, in ground | 2.68E+05 | 0.0025% | 6.64E+08 | 2.2% | 3.83E+08 | 1.1% | 4.10E+08 | 1.4% | 2.69E+08 | 1.2% | 7.27E+08 | 0.7% |
| Praseodymium, in ground | 2.39E+05 | 0.0023% | 0.00E+00 | 0.0% | 1.10E+08 | 0.3% | 7.17E+07 | 0.2% | 3.36E+07 | 0.1% | 5.72E+08 | 0.6% |
| Selenium, in ground | 1.85E+05 | 0.0017% | 3.97E+07 | 0.1% | 1.05E+08 | 0.3% | 5.62E+07 | 0.2% | 2.50E+07 | 0.1% | 5.12E+09 | 5.1% |
| Samarium, in ground | 6.41E+04 | 0.00061% | 0.00E+00 | 0.0% | 3.57E+06 | 0.0% | 2.88E+06 | 0.0% | 1.41E+06 | 0.0% | 1.44E+07 | 0.0% |
| Gallium, in ground | 5.68E+04 | 0.00054% | 7.70E+07 | 0.3% | 2.10E+08 | 0.6% | 1.11E+08 | 0.4% | 4.93E+07 | 0.2% | 4.83E+10 | 48% |
| Gold, in ground | 4.16E+04 | 0.00039% | 2.51E+09 | 8.5% | 3.39E+09 | 10.0% | 2.29E+09 | 7.6% | 1.75E+09 | 7.6% | 1.49E+09 | 1.5% |

| Inventory flows | Inventory (kg) | % | Endpoint totals (kg Fe-eq.) | | | | | | | | | |
|-----------------------|----------------|-----------|-----------------------------|------|----------|------|----------|------|----------|------|----------|------|
| | | | ReCiPe 2016 | % | LPST25 | % | LPST100 | % | LPST500 | % | ADR | % |
| Tellurium, in ground | 3.40E+04 | 0.00032% | 1.03E+07 | 0.0% | 3.85E+07 | 0.1% | 2.06E+07 | 0.1% | 9.20E+06 | 0.0% | 1.58E+09 | 1.6% |
| Gadolinium, in ground | 3.05E+04 | 0.00029% | 0.00E+00 | 0.0% | 6.69E+06 | 0.0% | 4.33E+06 | 0.0% | 2.02E+06 | 0.0% | 3.78E+07 | 0.0% |
| Yttrium, in ground | 2.82E+04 | 0.00027% | 0.00E+00 | 0.0% | 5.22E+06 | 0.0% | 3.21E+06 | 0.0% | 1.49E+06 | 0.0% | 2.87E+07 | 0.0% |
| Strontium, in ground | 1.71E+04 | 0.00016% | 2.42E+04 | 0.0% | 9.66E+04 | 0.0% | 5.89E+04 | 0.0% | 2.73E+04 | 0.0% | 5.62E+05 | 0.0% |
| Platinum, in ground | 1.35E+04 | 0.00013% | 1.92E+09 | 6.5% | 1.54E+09 | 4.6% | 1.26E+09 | 4.2% | 7.76E+08 | 3.4% | 2.25E+09 | 2.2% |
| Tungsten, in ground | 1.29E+04 | 0.00012% | 1.63E+06 | 0.0% | 2.88E+06 | 0.0% | 1.86E+06 | 0.0% | 8.64E+05 | 0.0% | 1.66E+07 | 0.0% |
| Europium, in ground | 1.20E+04 | 0.00011% | 0.00E+00 | 0.0% | 2.02E+07 | 0.1% | 1.16E+07 | 0.0% | 5.25E+06 | 0.0% | 2.23E+08 | 0.2% |
| Tantalum, in ground | 1.06E+04 | 0.00010% | 9.05E+06 | 0.0% | 1.03E+07 | 0.0% | 7.39E+06 | 0.0% | 3.55E+06 | 0.0% | 4.26E+07 | 0.0% |
| Arsenic, in ground | 9.79E+03 | 0.00009% | 2.07E+04 | 0.0% | 4.42E+04 | 0.0% | 2.42E+04 | 0.0% | 1.09E+04 | 0.0% | 6.32E+05 | 0.0% |
| Palladium, in ground | 9.49E+03 | 0.00009% | 6.56E+08 | 2.2% | 4.26E+08 | 1.3% | 3.93E+08 | 1.3% | 2.25E+08 | 1.0% | 9.10E+08 | 0.9% |
| Dysprosium, in ground | 7.70E+03 | 0.00007% | 0.00E+00 | 0.0% | 1.07E+07 | 0.0% | 7.17E+06 | 0.0% | 3.37E+06 | 0.0% | 5.47E+07 | 0.1% |
| Cadmium, in ground | 7.46E+03 | 0.00007% | 3.86E+04 | 0.0% | 1.31E+05 | 0.0% | 9.07E+04 | 0.0% | 4.32E+04 | 0.0% | 5.65E+05 | 0.0% |
| Terbium, in ground | 4.62E+03 | 0.00004% | 0.00E+00 | 0.0% | 1.64E+07 | 0.0% | 1.02E+07 | 0.0% | 4.73E+06 | 0.0% | 1.03E+08 | 0.1% |
| Lithium, in ground | 2.48E+03 | 0.00002% | 1.95E+05 | 0.0% | 5.56E+04 | 0.0% | 3.64E+04 | 0.0% | 1.71E+04 | 0.0% | 2.68E+05 | 0.0% |
| Rhodium, in ground | 1.78E+03 | 0.00002% | 1.83E+08 | 0.6% | 3.89E+08 | 1.2% | 3.41E+08 | 1.1% | 1.88E+08 | 0.8% | 9.01E+08 | 0.9% |
| Beryllium, in ground | 5.12E+02 | 0.000005% | 6.34E+05 | 0.0% | 4.78E+05 | 0.0% | 6.39E+05 | 0.0% | 3.46E+05 | 0.0% | 1.84E+06 | 0.0% |
| Antimony, in ground | 3.50E+02 | 0.000003% | 3.23E+03 | 0.0% | 1.29E+04 | 0.0% | 1.01E+04 | 0.0% | 4.96E+03 | 0.0% | 4.58E+04 | 0.0% |
| Vanadium, in ground | 2.90E+02 | 0.000003% | 1.86E+04 | 0.0% | 4.71E+04 | 0.0% | 2.86E+04 | 0.0% | 1.36E+04 | 0.0% | 1.94E+05 | 0.0% |
| Rhenium, in ground | 2.44E+02 | 0.000002% | 2.09E+06 | 0.0% | 5.29E+06 | 0.0% | 3.76E+06 | 0.0% | 1.82E+06 | 0.0% | 1.99E+07 | 0.0% |
| Mercury, in ground | 8.70E+01 | 0.000001% | 1.26E+04 | 0.0% | 1.94E+04 | 0.0% | 1.17E+04 | 0.0% | 5.39E+03 | 0.0% | 1.39E+05 | 0.0% |

6.3.3 Comparison of absolute impacts for all market data sets

Figure 6-4 shows the total impact scores for the 45 studied metals across all market data sets from the ecoinvent version 3.1.7 database. A single data set from section E with a negligible contribution for all impact categories was removed from graphs to improve their display. Please note that X- and Y-axes are shown with a log scale, and that the scale of the X-axis may vary amongst graphs.

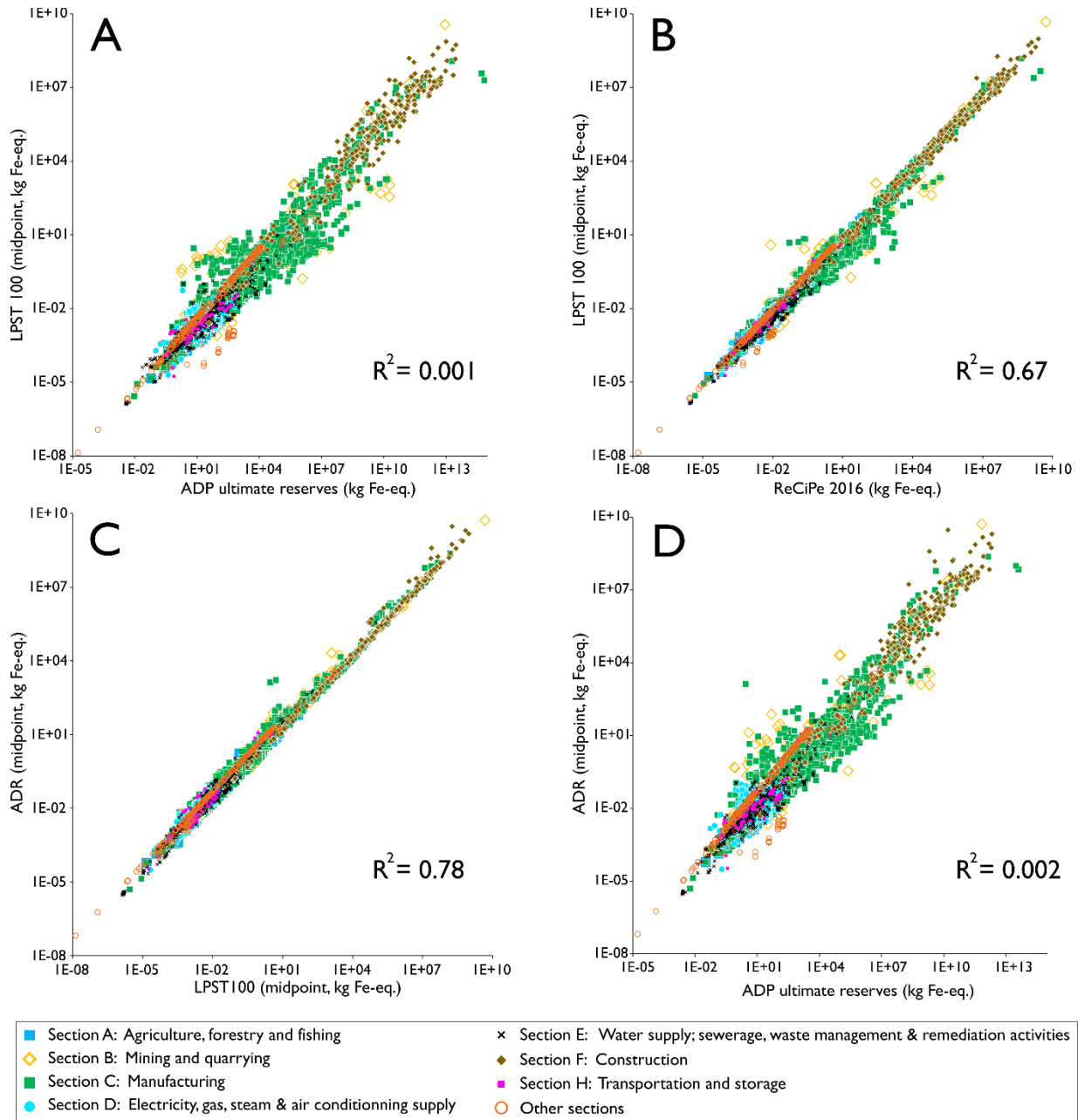


Figure 6-4. Comparison of impact assessment for selected pairs of LCIA methods, covering 5 998 market data sets organized by section of economic activity. All impacts scores are measured in kg Fe-eq. Degree of correlation (R^2) for the impact scores of all of the data sets are indicated on the graphs. A: *midpoint LPST100 vs ADP*; B: *midpoint LPST100 vs ReCiPe 2016*; C: *midpoint ADR vs LPST100*; D: *midpoint ADR vs ADP*.

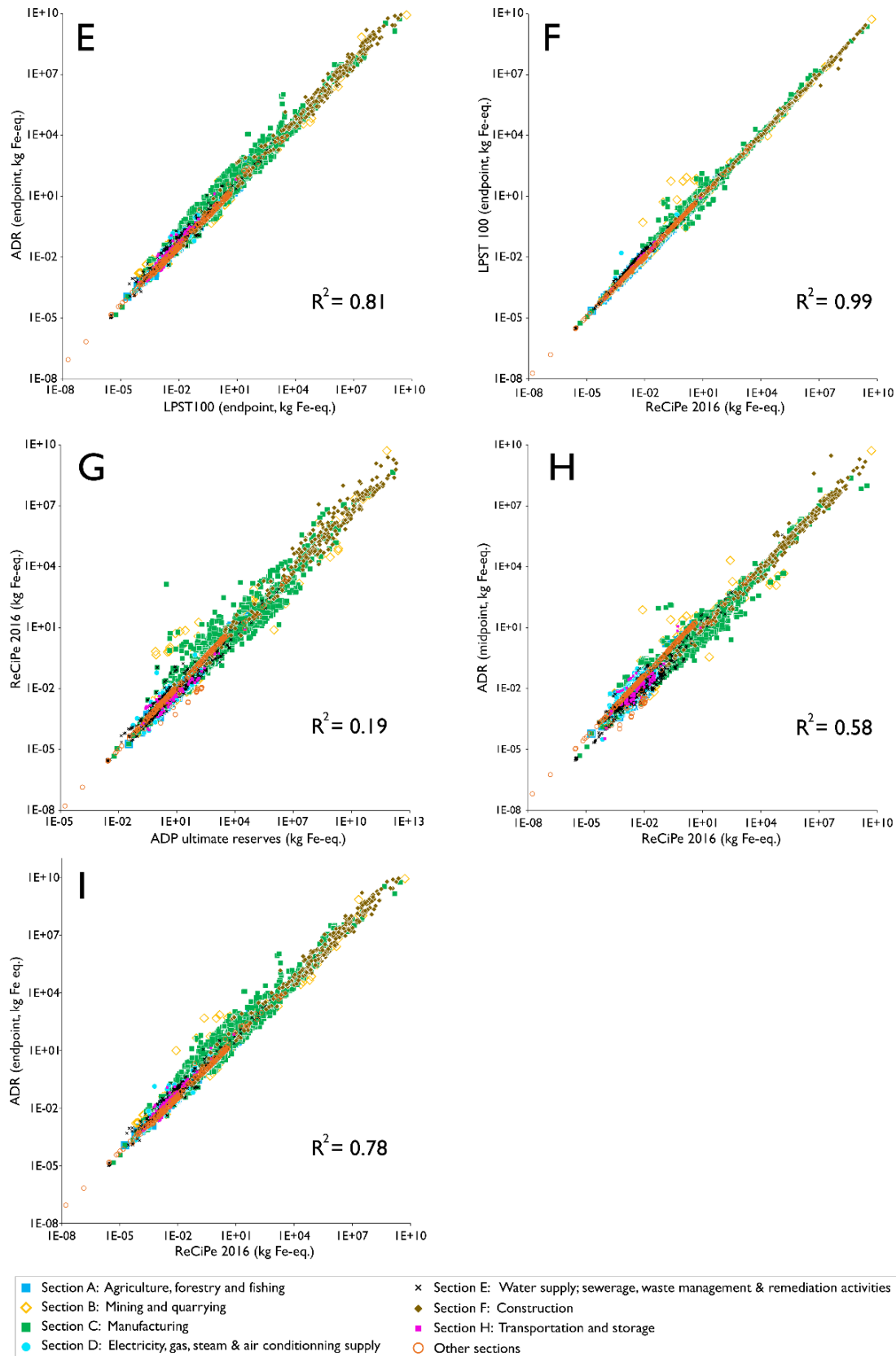


Figure 6-4 (continued). Comparison of impact assessment for selected pairs of LCIA methods, covering 5 998 market data sets organized by section of economic activity. All impacts scores are measured in kg Fe-eq. Degree of correlation (R^2) for the impact scores of all of the data sets are indicated on the graphs. *E*: endpoint ADR vs LPST100; *F*: endpoint LPST100 vs ReCiPe 2016; *G*: midpoint ReCiPe 2016 vs ADP; *H*: midpoint vs ReCiPe 2016; *I*: endpoint ADR vs ReCiPe 2016.

The impact scores range over 18 orders of magnitude across the data sets, which is largely explained by the large differentiation between functional units for each data set and corresponding flows of extracted resources: the sum of metal resource flows for the 45 studied metals spread over 9 orders of magnitude across the 5 999 data sets.

The impact scores for the midpoint ADR (i.e., the total dissipation rate, "TDR"; cf. Chapter 5) and the midpoint LPST100 (i.e., the total LPST at a time horizon of 100 years, "TLPST100"; cf. Chapter 5) methods, as shown in Figure 6-4C, are rather well correlated ($R^2 = 0.78$) given the similarities between the underlying data used for their computation, and that their CFs rank almost exactly the same across metals (cf. Chapter 5). For this reason, the scatter plots between these two methods and those of ADP are quite similar, as can be seen in Figure 6-4A (LPST 100 midpoint versus ADP; $R^2 = 0.001$) and Figure 6-4D (ADR midpoint versus ADP; $R^2 = 0.002$). The latter graphs show that data sets responsible for most impacts for the ADP ultimate reserves are likely to be much different than those for the ADR and LPST methods. This can be explained by the important differences in the hotspots for the contributions of different metals between these methods, as highlighted in section 6.3.2. Of course, these differences are linked to the different models aiming to answer different problematics linked to mineral resource use.

The endpoint ADR and LPST100 results are similar to their respective midpoints, as can be observed by comparing Figure 6-4C ($R^2 = 0.78$) and Figure 6-4E ($R^2 = 0.81$). While the price index has a strong influence on the endpoint CFs for the former method for those metals with relatively high dissipation rates, leading to rapidly increasing total impact scores for data sets for which even small fractions of highly dissipative metals with a high price index are utilized when using the endpoint ADR CFs, resource flows for these metals are only rarely significant amongst the data sets. For instance, gallium's average flow is of 9.5 kg across data sets while its median is of 1.5E-07 kg. Therefore, the high contribution of gallium to total endpoint impacts for the ADR method, as shown in Figure 6-3, is due to a few data sets with a disproportionate representativeness in this study because of the way the study was led. This limitation could be circumvented by recalibrating functional units, as realized by Rørbech et al. (2014) through a step-wise rescaling approach, which could be the object of future works.

The total impact scores for the LPST100 midpoint method, i.e., TPLST100, are much better correlated with results for ReCiPe 2016 (Figure 6-4B; $R^2 = 0.67$) than those for ADP (Figure 6-4-A; $R^2 = 0.001$). Logically, ReCiPe's impact scores are also rather poorly correlated with ADP's (Figure 6-4-G; $R^2 = 0.19$). The most notable divergences can be observed between TLPST100 and ADP scores for sections C: Manufacturing, D: Electricity, gas, steam & air conditioning supply, and F: Construction. These observations can be explained by the stronger convergence between the ranking of CFs for the

LPST100 and ReCiPe methods than ADP's, as shown in Table 6-1. In addition, the very high differentiation between CFs for the ADP method leads to acute hotspots for a few single metals despite their very small resource flows in the inventory, as seen in section 6.3.1. This phenomena is less important for the ADR, LPST and ReCiPe methods as their CFs are less differentiated. Finally, the comparison between endpoint category totals for the LPST100 method (i.e., LPV100) and those of ReCiPe 2016 method shows an even higher convergence between them than for the midpoint assessment (Figure 6-4F; $R^2 = 0.99$). A plausible explanation for such convergence was identified in the last paragraph of section 6.3.2.

6.4 Conclusion

In Chapter 5, CFs have been developed for two methods taking into account the global dissipation patterns of 61 metals over their global anthropogenic cycle: the ADR and LPST methods. Endpoint CFs for these methods additionally provide indications on the potentially lost value due to the dissipation of metals. As demonstrated with the large scale application study, the ADR and LPST methods can be readily used in LCA studies, providing information on the global dissipation profiles of different metals and on dissipation's potential socio-economic damage for humans globally, as accounted for in the AoP natural resources.

We compared impact assessment results for 5 999 data sets for the ADR and LPST methods with that of widely used LCIA methods: the ADP ultimate reserves, as well as the (midpoint) SOP and (endpoint) SCP methods included in ReCiPe 2016. Our analysis showed the degree to which midpoint impact assessments could diverge between the ADR, LPST100, and the ReCiPe 2016 and ADP ultimate reserves methods. Results for the ADR and LPST100 methods were best correlated amongst midpoint assessments ($R^2 = 0.78$). Those for the ADP ultimate reserves were the least correlated with results for the ADR ($R^2 = 0.002$) and LPST100 methods ($R^2 = 0.001$), suggesting that the dissipation rates of metals after extraction are generally not aligned with their depletion potentials. As seen in Chapter 4, the dissipation rates are dependent on process yields across all life cycle phases as well as the lifetimes of applications. In contrast, the depletion potentials are calculated as the ratio between yearly extraction and the squared ultimate reserves, computed as a fraction of the crustal content in the ADP ultimate reserves method (van Oers et al., 2019, 2002), and the SOP method (midpoint method for ReCiPe 2016), the surplus ore to be extracted in the future due to current extraction (Vieira et al., 2017).

It was shown that different metals can be expected to underlay impact hotspots amongst the studied LCIA methods. Gold, palladium, platinum and tellurium were recurrently important contributors to the ADP ultimate reserves impact assessments given their high extraction to ultimate reserves ratio. Notably, gold is expected to be amongst the most impactful metals for all sections of economic activity

(Figure 6-2). Moreover, copper is also expected to be an important contributor to ADP results because it has a relatively small crustal concentration (0.0028%) in comparison to other widely extracted metals contributing most to inventory totals (e.g., 0.063% for barium, and 0.077% for manganese, as reported by van Oers et al., 2019). In contrast to ADP, precious metals gold, palladium and platinum were only expected to represent a large share of total impact for section C using the ReCiPe 2016 method. Using the latter method, iron recurrently came up as a main contributor, with at least 10% of impacts totals for all sections of economic activity except section C. Copper also had a significant contribution to the ReCiPe 2016 impact assessment for sections D, E and F; and so did zinc for sections F and H. Like for ReCiPe 2016, widely extracted metals are more likely to come up as main contributors to midpoint impact assessment using the LPST and ADR methods. Indeed, the top contribution for the latter methods across sections of economic activities was iron, as well as barium for most sections of economic activity, and to a lesser extent, zinc (section C and other sections), and magnesium (other sections).

A notable result from this study was that the endpoint assessment using the LPST100 method correlated well to those of ReCiPe 2016 ($R^2 = 0.99$). As shown in Figure 6-3, these endpoint methods are about as sensitive to the relative shares of inventory totals for iron, copper, gold and nickel. It is apparent that, like for extraction, the dissipation of scarcer metals is costlier for society because they require more additional ore to produce, as accounted for in the midpoint SOP method, and consequently are also more costly to produce, as accounted for in the endpoint SCP method. The cost of production is also reflected in the price index underlying the computation of endpoint CFs for the ADR and LPST methods.

The impact pathways addressed by the ADP ultimate reserve, ReCiPe 2016, and ADR or LPST methods answer different questions related to mineral resource use (cf. Berger et al., 2020). Using the terminology of the MR taskforce (Berger et al., 2020), the ADR and LPST methods allow evaluating the lost potential to make use of the value of mineral resources due to dissipation. The ADP ultimate reserves method allow evaluating the lost potential to make use of the value of resources due to the depletion of ultimate reserves. The SOP method allow evaluating the relative consequences of the contribution of a product system to changing mineral resource quality, and the SCP, the lost potential to make use of the economic value of mineral resources due to changing mineral resource quality. These methods are potentially complementary and could eventually be assessed altogether in LCA studies; however, as discussed in Chapter 2, additional efforts will be needed to assess the impacts of mineral resources using multiple LCIA methods. Finally, we remind that the limitations identified in Chapter 5 should be kept in mind during the interpretation of LCIA results using the ADR and LPST

methods, as it should be done for any other LCIA method. Some perspectives for improving the methods and their application in LCA studies are discussed in Chapter 7.

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Chapter 7. Discussion and conclusion

This chapter is split in five sections. In the first section, the advances proposed in this thesis with regards to the objectives identified in Chapter 1 are presented. In the second section, the developed average dissipation rate (ADR) and lost potential service time (LPST) methods are compared against five criteria from the International Reference Life Cycle Data System (ILCD) handbook. In the third section, perspectives for the assessment of the dissipation of mineral resources with the ADR and LPST methods are explored. In the fourth section, a discussion on pursuing a more comprehensive assessment of multiple impact pathways addressing mineral resource use in life cycle assessment (LCA) is provided. Finally, the outlooks for the works accomplished during this thesis are presented as a general conclusion in the fifth section.

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7.1 Response to the objectives

The work done in this thesis aimed to develop a method to account for the dissipation of mineral resources in LCA. The research question was: "Can life cycle impact assessment methods be developed to assess the impacts of the dissipation of mineral resources on the area of protection natural resources, in a complementary way to other impact assessment methods?". Coherently, the research hypothesis was that "LCIA methods can be developed in order to account for the dissipation of mineral resources with the framework of LCA, and these methods can be linked to the AoP natural resources in a way that is consistent with other LCIA methods". Underlying this hypothesis, five sub-objectives were identified in the Introduction (**Chapter 1**).

The first sub-objective (**Chapter 2**) was to identify impact pathways for mineral resource use and their linkage to the safeguard subject for the area of protection natural resources proposed by the Life Cycle Initiative's taskforce on mineral resources. The proposed developments showed that resources were accessed by specific potential users for their economic value along supply chains, and their use values as parts of products. Impact pathways were evaluated against cultural perspectives and their socio-economic objectives, revealing that different aspects of resource use may be relevant to different perspectives, and therefore that impact assessment could vary for each of them. The impact pathway for the dissipation of mineral resources was therefore put into the context of using multiple LCIA methods for the AoP natural resources.

The second sub-objective (**Chapter 3**) was to identify challenges to account for the dissipation of mineral resources in LCA and to propose a conceptual framework to do so. The state of the art presented a definition of dissipation and explored a few connected issues: the different definition of resources for different stakeholders, the constraints to access mineral resources, and the effects of the time horizon. Furthermore, two options were identified as ways forward to account for dissipation based on dynamic MFA data: updating LCI databases or propose CFs applicable to extraction flows in the inventories that integrate the expected dissipation patterns for different mineral resources. The second option was preferred and the remaining of the thesis built upon it.

The third sub-objective was to generate dynamic MFA data needed to develop characterization factors (CFs) to account for the dissipation of mineral resources in life cycle assessment (**Chapter 4**). A wide data collection phase and dynamic MFA model allowed obtaining dynamic MFA results for 61 metallic elements, including an uncertainty assessment. We computed the loss rates and lifetimes of these metals in the economy, and simulated the evolution of stocks of metals over time across 41 end use sectors. Moreover, we attributed the cumulative losses of metals to one of five main life cycle phases: production, fabrication and manufacturing, use, collection and sorting, and recycling.

The fourth sub-objective was to develop LCIA methods and their respective CFs that can be used in LCA studies (**Chapter 5**). Two methods were proposed: the ADR and the LPST. Using the dynamic MFA results from Chapter 4, CFs could be computed for 61 metallic elements. Moreover, endpoint CFs for both methods were computed by multiplying midpoint CFs with a price index. The relative price of metals allows distinguishing between metals of lower and higher value for humans, the idea being that dissipating metals of lesser value is less problematic than higher value ones. These new LCIA methods are meant to be applied to resource (extraction) flows in the LCI.

The fifth and last sub-objective was to realize a case study using the developed CFs (**Chapter 6**). The study was led by applying CFs from the ADR and LPST methods to 5 999 market datasets from the ecoinvent database, along with those of popular characterization models: ADP ultimate reserves and ReCiPe 2016. The study revealed that the hotspots of impact assessments for the dissipation of mineral resources are expected to be quite different from the impacts characterized by the other LCIA methods. As presented in Chapter 2, the methods answer different questions related to mineral resource use, and may thus be complementary for the assessment of mineral resource use on the AoP natural resources.

7.2 Evaluation of the ADR and LPST methods against five criteria

The main output of this thesis is the set of CFs developed for assessing the impacts of the dissipation of mineral resources (metals), through the use of the ADR and the LPST methods. In sections 7.2.1 to 7.2.5, we evaluate the ADR and LPST methods against five scientific criteria proposed to evaluate life cycle impact assessment (LCIA) methods in the ILCD handbook (European Commission, 2010).

7.2.1 Completeness of scope

The CFs for the ADR and LPST methods allow differentiating between the dissipation profiles of 61 metallic elements from extraction and throughout their global anthropogenic cycle. The methods cover most commercially relevant metals, including some not yet accounted for in the ecoinvent database. Still, in order to cover all abiotic resources, additional efforts would be needed to cover mineral compound flows (e.g., fluorine, sand, and talc), as well as fossil fuels and their derived products like plastics. Furthermore, the CFs are computed with a global scope, which may be most relevant for commodities traded worldwide (Schulze et al., 2020). LPST25, 100 and 500 allow for using different time horizons in the assessment. No discounting is applied; however, different time horizons could be used for the assessment of different elementary flows depending on one's cultural perspective (as proposed in Chapters 2 and 5, and further discussed in section 7.3.2 below).

7.2.2 Relevance for the assessment of mineral resource use on the AoP natural resources

Given the most recent advances regarding the understanding of mineral resource use in the AoP natural resources, we replaced the "Environmental relevance" criteria from the ILCD handbook with that shown in this sub-section's title. The midpoint and endpoint CFs for the ADR and LPST methods have the advantageous feature only to rely on real-life process yields and product lifetimes considering as recent technologies as possible, allowing to use concrete time horizons in the assessment. They allow comparing between the dissipation profiles of 61 metals and their potential impacts on the safeguard subject for mineral resources as defined by the taskforce Mineral resources of the Life Cycle Initiative, i.e., "the potential to make use of the value that mineral resources can hold for humans in the technosphere" (Berger et al., 2020). The endpoint CFs allow quantifying the lost potential value due to dissipation caused by human activity. Using the terminology from the taskforce mineral resources (Berger et al., 2020), they answer the following question: "how can I quantify the relative contribution of a product system to the dissipation of mineral resources?".

7.2.3 Scientific robustness and certainty

The midpoint and endpoint CFs for the ADR and LPST methods rely on real-life process yields and product lifetimes, allowing to use concrete time-related information in the assessment (i.e., dissipation rates for ADR, and time horizons for LPST). The most up-to-date data were gathered to compute the underlying dynamic MFA results (Annex B). Moreover, the uncertainty is evaluated based on the underlying data quality, and CFs are computed with a 95% confidence interval.

7.2.4 Documentation, Transparency, and Reproducibility

In chapter 4, we provided an updatable, machine-readable dataset that is runnable with a MaTrace-like model (Helbig et al., 2020; Nakamura et al., 2014) coded in Python. The data has been thoroughly explained and documented, with each single data point being detailed and referenced in the Supporting information provided in Annex B. The dataset and Python code for the MaTrace model have been provided in the ODYM format (Pauliuk and Heeren, 2019), and will be made freely available online along with the submitted article once published. Thus, given that updated data become available for different metallic elements, the MaTrace model can be fed with new data to ensure that the dynamic MFA results underlying the computed CFs remain as up-to-date as possible. For example, a regular literature monitoring (e.g., every 3 to 5 years) could allow updating process yields and end-use distributions. Similarly, price statistics could be updated regularly as to reflect most recent trends; however, these may require the access to undisclosed statistics in a few instances. Finally, it would be possible for third-party users to generate CFs for additional mineral resources by using available materials and methods presented above.

7.2.5 Applicability

CFs are available and readily applicable for 61 metals. They could be integrated into widely used LCA software to assess the impacts of dissipation in LCA. The methods are currently meant to be applied to extraction flows given missing dissipative flows in widespread databases, but they might be applicable to dissipative (or loss and/or waste) flows in the future, as discussed in Chapter 5. Their applicability has been demonstrated through their application to 5,999 datasets from ecoinvent version 3.7.1 database, which includes 45 metal flows that can be characterized with the CFs provided for 61 metals (Chapter 6).

It should be noted that elementary flows of these metals are not consistently accounted for in widespread LCI databases, especially for by-products such as gallium and scandium, which could be detrimental to an exhaustive and accurate assessment of the impacts of mineral resource use on the AoP natural resources in LCA. For instance, 16 out of 61 metals for which we computed CFs do not have their corresponding elementary flows reported in the ecoinvent 3.7.1 database. Further research is needed to evaluate the applicability of the ADR and LPST methods with other databases.

7.3 Perspectives for the ADR and LPST methods

A few general perspectives to improve the ADR and LPST methods can be identified. Additional CFs could be developed for other minerals such as construction aggregates, sand, etc. Our publicly available framework and methods (Chapter 4 and Annex B) could support the computation of these CFs with a consistent methodology. Furthermore, additional research is needed to improve the characterization of the economic and use value of mineral resources, as investigated in Chapter 2. A different methodology could be developed to evaluate endpoint damage in a more reliable way than by using resource prices. Finally, efforts could be spent on developing CFs considering different assumptions on the future recovery of metals from, e.g., final waste disposal facilities (see e.g. Dewulf et al., 2021). Such assumptions could build on different cultural perspectives, as discussed in Chapter 2. In the two sub-sections below, we discuss how the CFs from the ADR and LPST methods could potentially be applied to dissipative flows (DFs) rather than extraction flows, and how different future recovery scenarios could be implemented in such an assessment under different cultural perspectives.

7.3.1 Applying CFs from the ADR and LPST methods to DFs rather than extraction flows

While the CFs of the ADR and LPST methods are meant to be applied to extraction flows with the current LCI, they could be adapted to be applied to DFs instead. This would become handy if DFs were to be properly accounted for in LCI databases in the future, or if they are systematically identified through additional offline manipulations of LCIs, as proposed by Beylot et al. (2021). Alternatively, it is

possible to estimate DFs by taking the functional end-of-life recycling of metals of a studied system into account. DFs are then equal to metal resource inputs minus functionally recycled outputs: the lightened resource flows in the modified inventories can then be multiplied with the ADR or LPST CFs to assess the impacts of dissipation. Ultimately, it would be most useful if DFs were properly accounted for in LCI databases (Beylot et al., 2020b). Potential options to characterize DFs as accounted for in the LCI are discussed in the next sub-section.

7.3.2 Considering periods of inaccessibility for the assessment of the impacts of dissipation under different cultural perspectives

The effect on time on the assessment of dissipation is important for two main reasons. First, time horizons are needed to identify which flows are identified as dissipative, since some flows may be recoverable in the future (Beylot et al., 2021, 2020a; Dewulf et al., 2021; Owsianiak et al., 2021). Second, the relevant time horizon and associated impacts may depend on one's cultural perspective, e.g., egalitarian, hierarchist, or individualist (cf. Chapter 2). The ADR and LPST methods integrate time in the assessment: the former, as an average speed of dissipation, and the latter, with a time horizon-based inaccessibility. The resolution of time in static LCI databases has long been discussed and may be a limitation to assess such time-dependent issues (Lueddeckens et al., 2020). This may be an issue, as the inaccessibility of resources should be measured over time (Dewulf et al., 2021).

In their review, Lueddeckens et al. highlight that the LCA community mostly interpreted the selection of time horizons as a subjective political decision. In this context, we proposed three time horizons for the impact assessment using the LPST method: 25, 100 and 500 years. These could be thought to roughly correspond to the individualist, hierarchist, and egalitarian perspectives, respectively (Chapter 2). As a reminder, these perspectives originate from the Cultural Theory (Thompson et al., 1990) and have been used to support modelling choices in the Eco-indicator 99 method (Goedkoop and Spriensma, 2001), later assimilated by the ReCiPe 2008 and 2016 methods (Goedkoop et al., 2013; Huijbregts et al., 2017).

Considering that DFs of resources could be identified distinctively as elementary flows in LCIs (e.g., resource flows to the environment [emissions], or resource flows to final waste disposal facilities [waste flows]), it would be possible to fine-tune the impact assessment by using different LPSTs for different flows depending on subjective beliefs on human development and future societies. We here briefly discuss how the assessment could be differentiated between cultural perspectives, following the discussion in Chapter 2. It should be noted that the LCI would need to include a time-dependent inaccessibility (equivalent to land use change) in order to assess the relative contribution of different loss flows to the global inaccessibility of resources over time, as measured with the LPST method.

Egalitarians tend to privilege the long term and are rather pessimistic about technological developments and human capacity to adapt to a changing environment. Therefore, the egalitarian assessment could consider that both the flows to the environment and to waste disposal facilities will remain inaccessible over the next 500 years, and characterize all of the loss flows with the CFs of the LPST500 method as currently proposed. Hierarchists are interested in the short to long term, and believe in the capacity of humans to adapt through the development of the man-made environment. Their assessment could thus take into account that resources dissipated in the environment will not be accessible over the next 500 years, but could estimate that resource flows ending in landfills will become accessible in, e.g., 100 years, and those in tailings, in, e.g., 50 years. Therefore, CFs following the hierarchist perspective could be recalculated by including future recovery scenarios in the dynamic MFA model. However, as mentioned previously, these updated CFs should be applied to time-resolved inaccessibility information provided by the LCI. Finally, the individualistic assessment could consider the short-term impacts of dissipation, and apply the CFs from the LPST25 method to resource flows ending in the environment and landfills. A theoretical exercise showing the inaccessibility of a metal over time due to a product system (inspired from Dewulf et al., 2021), as well as the assessment of its impacts over the time horizon of 25 and 500 years, is presented in Figure 7-1 and Figure 7-2.

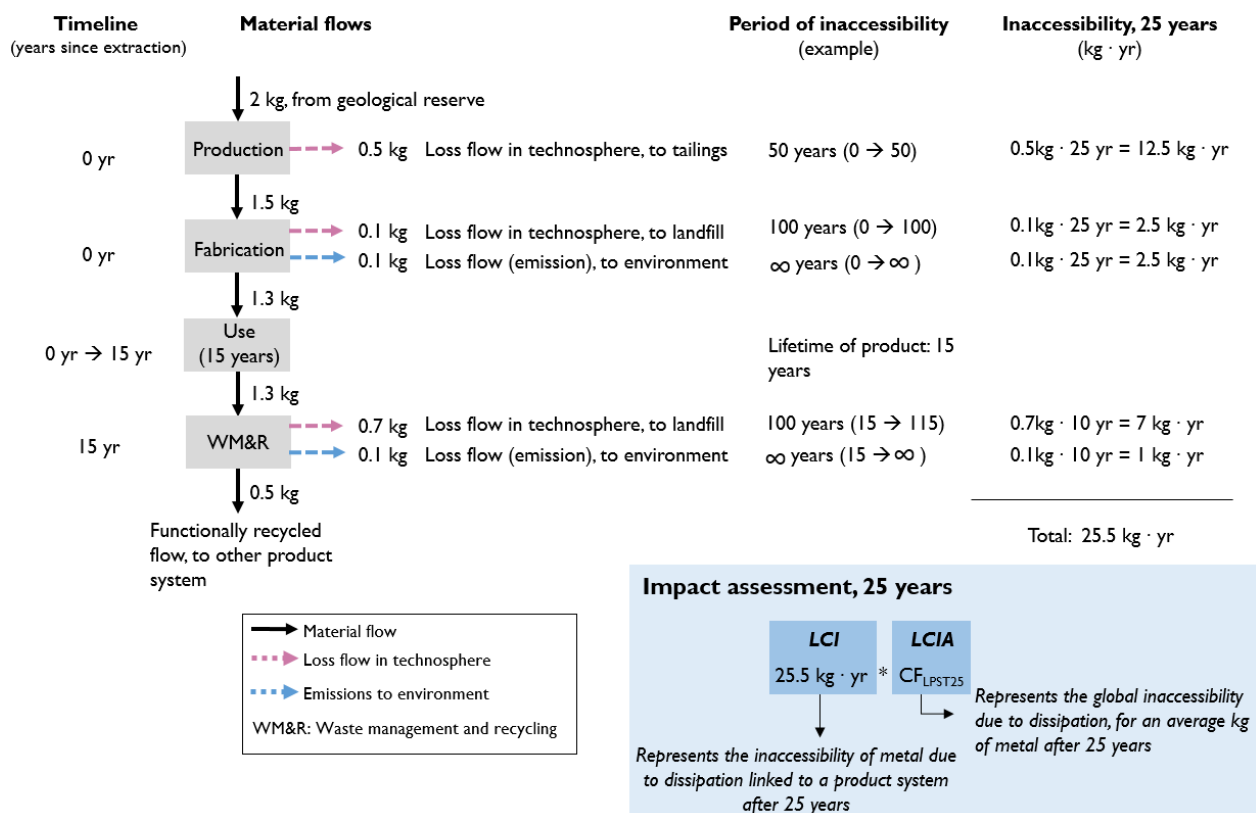


Figure 7-1. Theoretical example of the inaccessibility of a metal resource due to a product system at the time horizon of 25 years, and assessment of its impacts with the LPST25 method. The duration of inaccessibility is capped at 25 years.

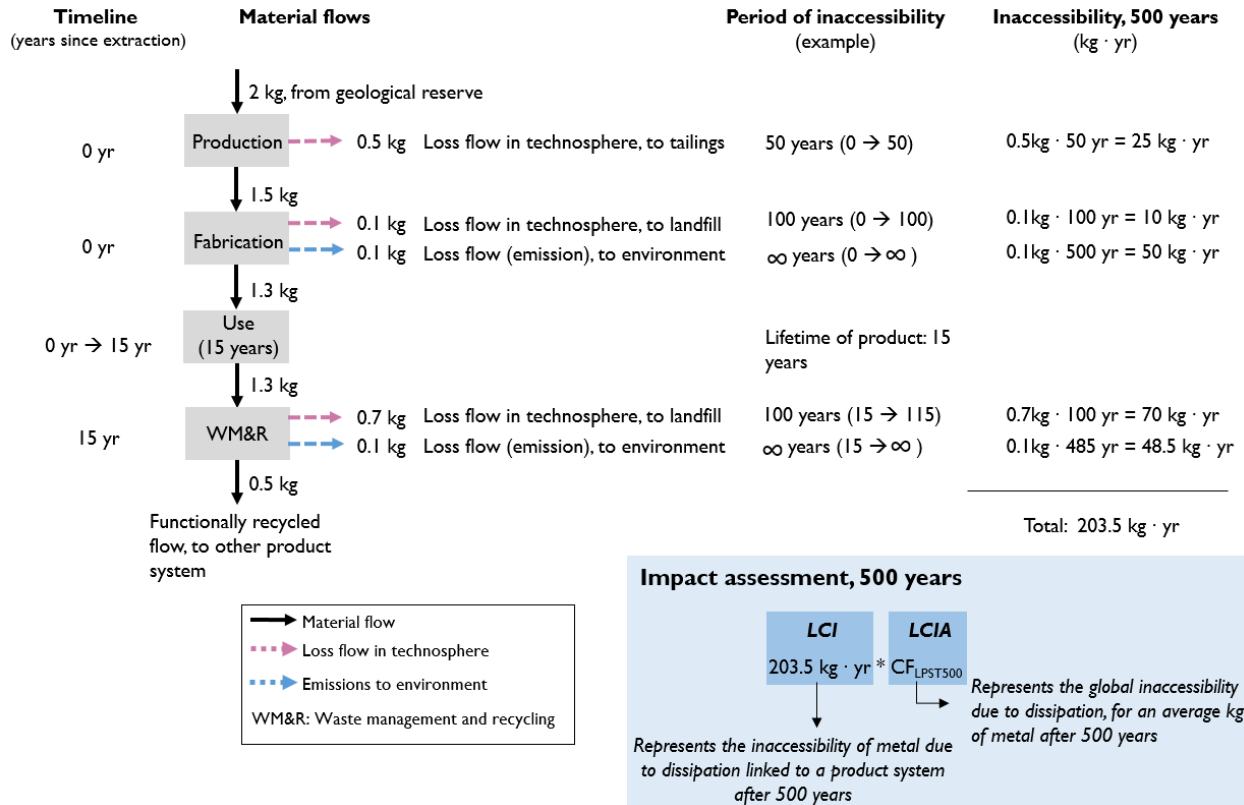


Figure 7-2. Theoretical example of the inaccessibility of a metal resource due to a product system at the time horizon of 500 years, and assessment of its impacts with the LPST500 method. The duration of inaccessibility is capped at 500 years.

As noted above, the dynamic MFAs underlying the computation of CFs for the LPST500 method in this second example (Figure 7-2) would need to be recalculated by including the future recovery of metals in the model. With these updated dynamic MFA results under different perspectives (or scenarios), specific CFs could then be computed for different loss flows of metals including the projected time length of their inaccessibility, which could be the object of future research. However, these additional considerations would also add complexity to updating the model and CFs. Moreover, given their prospective nature, the scenarios for future recovery should be plausible and well-argued and/or documented. The discussion by Dewulf et al. (2021) may provide a starting point for establishing such scenarios. Complementarily, different criteria could be used to evaluate which resources will become accessible over different time horizons, e.g., as proposed by Owsianiak et al. (2021) for environmental emissions. However, it should be noted that these tweaks to the methods would require bringing hefty modifications to the dynamic MFA model underlying the computation of CFs in order to track resource losses to specific sinks and stocks, which may be difficult to do for most metals given the availability of data. Assuming this is achievable, the future recovery from different sinks and stocks should be

implemented in the dynamic MFA model according to each the assumptions corresponding to different cultural perspectives.

An alternative option to account for the potential future recovery of different loss flows would be to generate different CFs that account for the estimated duration of the inaccessibility of loss flows, i.e., by multiplying the current CFs with an additional time parameter of inaccessibility of different loss flows. For example, if it is desired to assess the impacts of DFs over the next 500 years, the loss flows to landfills could first be multiplied by, e.g., 100 years (estimated period of inaccessibility for these flows), resulting in an assessment of inaccessibility measured in kg·yr, and then multiplied with the CFs of the LPST500 method. Following this idea, the same should be done for other loss flows: flows of resources to the environment (emissions) could be multiplied with, e.g., 500 years (estimated period of inaccessibility for these flows after 500 years), and then multiplied with the CFs of the modified LPST500 method, as discussed above, and so on for all of the different loss flows to different sinks and stocks. These additional time factors for inaccessibility could be implemented in the characterization method to account for different cultural perspectives as discussed above. This alternative option is shown in Figure 7-3.

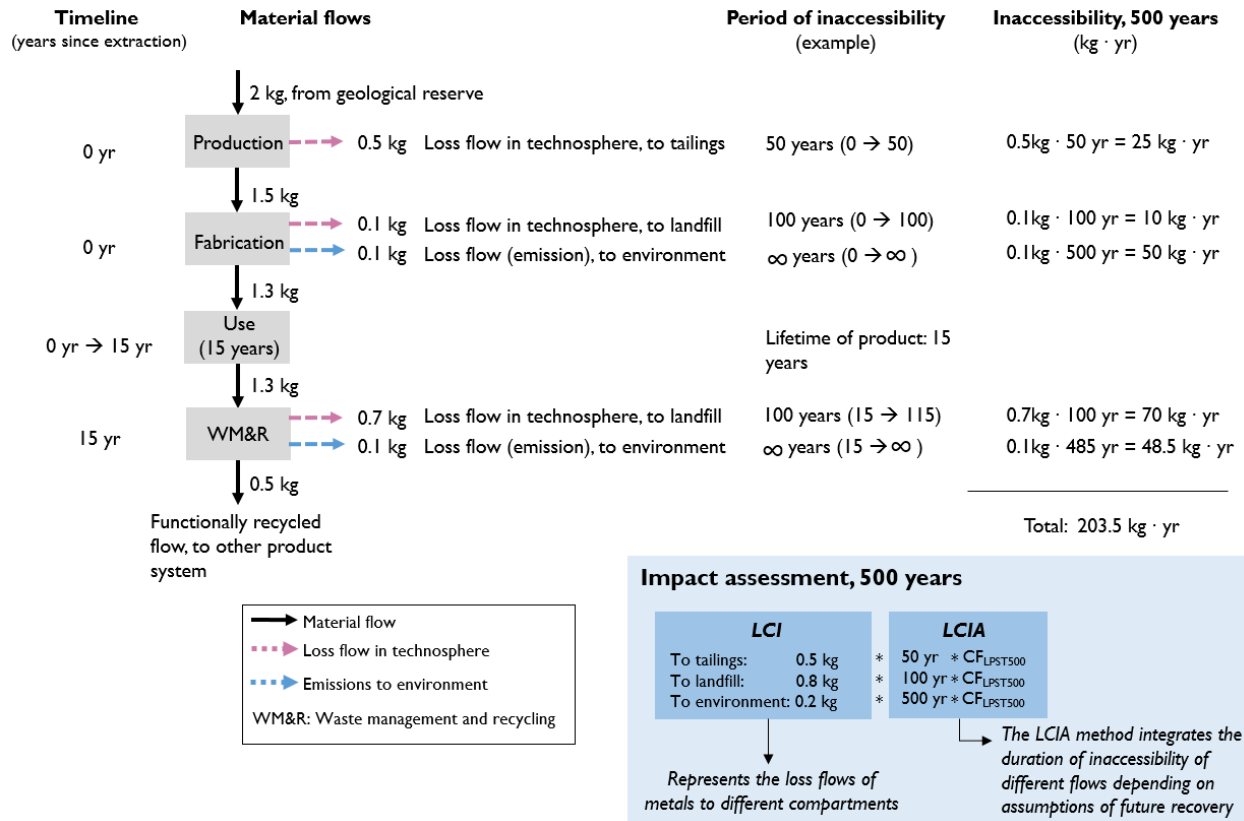


Figure 7-3. Theoretical example of the loss flows of resources due to a product system, and assessment of its impacts with a modified LPST method accounting for the duration of the inaccessibility of these loss flows.

The duration of inaccessibility is capped at 500 years.

7.3.3 Considering different values of loss flows for the endpoint assessment

Besides accounting for different periods of inaccessibility, generating flow-specific CFs for the LPST method would also allow valuing these flows differently. For example, waste flows to tailings could be attributed a lesser price index than waste flows to landfills, because the resources that are lost to tailings are generally of lesser concentration than those being landfilled given that no efforts were spent on beneficiating and refining them. Such considerations could be subject to future research.

7.3.4 The CFs of the midpoint ADR and LPST methods as indicators of circularity

The midpoint CFs for the ADR and LPST methods provide indications of the rate at which different metals are lost from the economy, and the resulting inaccessibility to these metals over time, respectively. As discussed in Chapter 5, dissipation (or losses) can be understood as the negation of circularity, since dissipated resources are inaccessible and thus do not provide their value to society. Interestingly, Moraga et al. (2021) developed circularity indicators at the product scale that follow a rationale that is analogous to that of the LPST method, however accounting for the in-use duration (i.e., the service time when using the terminology for the LPST method) rather than the LPST. Thus,

given that they were developed with a global scope, the midpoint CFs for the ADR or LPST methods could potentially be used as indicators of the circularity of metals at the global scale.

7.4 Towards a more comprehensive assessment of impacts linked to mineral resource use

In this section, the perspectives for assessing impacts of multiple aspects of mineral resource use in LCA are discussed.

7.4.1 Dissipation: a new impact pathway for mineral resources

New approaches have been developed to account for the dissipation of mineral resources in LCA. We here briefly discuss current approaches addressing dissipation in the LCI and LCIA phases.

7.4.1.1 Approaches to account for dissipation of mineral resources in the LCI

The impact assessment of the dissipation of mineral resources should be based on a proper accounting of dissipative flows in life cycle inventories (Beylot et al., 2020b; Zampori and Sala, 2017). The JRC have worked on a methodology to do so, relying on balancing input and output substance flows at the process level (Beylot et al., 2021, 2020a). However, the suggested approach requires heavy work from LCA practitioners, and dissipative flows would desirably be directly reported in life cycle inventory databases in the mid to long term (Beylot et al., 2020b). Moreover, outputs from the Abiotic Resources Project (ARP) project suggest distinguishing between dissipative and non-dissipative emissions of resources in the LCI by using two criteria: the concentration of metals in resources extracted from the environment, and the build-up concentration of metals in different environmental compartments from cumulative anthropogenic emissions (Owsianiak et al., 2021, in press). The reference concentration is the crustal content: if a metal is emitted from a source in which its concentration is below that of the crustal content, it is not considered as a dissipative emission of resources, and if its cumulative emissions over 500 years are predicted to build-up stocks in the environment that are greater than the crustal content, it is also not considered as a dissipative emission.

7.4.1.2 LCIA methods addressing the dissipation of mineral resources

In the short term, proxy methods may be used to assess the impacts of the dissipation of mineral resources in LCA (Beylot et al., 2020b). So far, three groups of researchers have proposed potential solutions. Firstly, the JRC suggested approach relying on accounting of dissipation at the process level, as outlined above, is then to characterize impacts by multiplying dissipative flows with CFs based on the economic value of resources (Beylot et al., 2020a). Secondly, the environmental dissipation potential (EDP) method allows to estimate the impacts of environmental dissipation based on current

emission flows in the inventories (van Oers et al., 2020). Thirdly, the ADR and LPST methods, as developed in this thesis, allow estimating the impacts of the dissipation of mineral resources based on extraction flows in the inventories, including losses to the environment and to final waste compartments in the technosphere.

If ever dissipative flows were accounted for properly in LCI databases in the future, the JRC suggested approach could possibly adapt by directly applying price-based CFs to dissipative flows accounted in the inventories. As discussed in section 7.3.2, the ADR and LPST methods could possibly be adapted to apply to dissipative flows rather than extraction flows. Finally, the EDP method might need to complement their approach to apply CFs only to dissipative flows of resources to the environment, instead of all emission flows, as proposed in the article to be published as an output of the ARP (Owsianiak et al., 2021).

7.4.1.3 Remaining challenge: resource quality

While it has been identified as a challenge to overcome over fifteen years ago (Stewart and Weidema, 2005), the quality of mineral resources is yet to be taken into account in LCI and LCIA methods. The challenge to overcome is to account for shifts in resource quality when, e.g., alloying elements become contaminants in larger material flows. For example, copper often becomes a detrimental contaminant in steel during recycling of EOL scraps. This situation implies the dissipation of copper, as well as the diminishing quality of its sink: the steel flow. While we addressed the part of the problematic linked with non-functional recycling in the ADR and LPST methods (e.g., in this case, of copper), the quality aspect was beyond what could be achieved in this thesis (e.g., in this case, the lowering quality of steel). Assessing resource quality should likely involve information provided by the LCI.

7.4.1.4 Accounting for the dissipation of other resource categories

Beyond the proper consideration of mineral resource use in LCA, the proposed LCIA methods based on functional dissipation using dynamic MFA data could possibly be translated to other resource consumption related challenges in LCA, such as the use of fossil fuels for plastics that has led to marine litter pollution, and the accumulation of space debris in orbits around the earth, currently not adequately taken into account in LCA. The phenomena leading to impacts is always the same: missing anticipation by humans of the potential damages due to dissipation of materials, including losses to natural reservoirs.

7.4.2 Towards measuring impacts of mineral resource use with complementary LCIA methods

The impact assessment of mineral resource use in LCA has traditionally considered a single impact pathway and related method. No clear definition of the safeguard subject for mineral resources in the AoP natural resources was available during past LCIA method development, and the latter were thus developed in an imprecise context, with diverging safeguard subjects. The long-lasting debate on how to consider the impacts of mineral resource use therefore mostly revolved around which single method and underlying modelling choices were most appropriate (e.g., which geological stock to consider). Recently, the Life Cycle Initiative's Taskforce proposed a clear definition of the safeguard subject and grouped existing LCIA methods based on seven potentially relevant aspects of mineral resource use that LCA practitioners could wish to address (Berger et al., 2020; Sonderegger et al., 2020). They recommended different LCIA methods aligned with each aspect.

Building on these new advancements of the taskforce, we further demonstrated that different impact pathways were in fact relevant to different views of the world in line with different models of socio-economic development scenarios (Chapter 2). We showed that LCA practitioners associating with a specific cultural perspective should consider multiple impact pathways relating with the said perspective, rather than picking out a single LCIA method answering some aspect that interests them. Still, some challenges will need to be faced to consider multiple impact pathways for a comprehensive assessment of mineral resource use, as discussed in the two following subsections.

7.4.2.1 *Harmonizing assessment using multiple methods within the AoP natural resources*

Some difficulties are expected to emerge when attempting to assess the impacts of mineral resource use with multiple LCIA methods at once, in an analogous way to other AoPs of human health and ecosystem quality. If all impact pathways to be addressed (cf. Chapter 2) were to measure endpoint damage in a common unit, e.g., dollars, it would be possible to straightforwardly sum these to assess the total damage on the AoP natural resources. However, it may be difficult to do so given the variety of mechanisms, time horizons and geographical scope underlying different impact pathways. For instance, supply risk methods assess the provisioning risk for a specific product or supply chain and its potential short-term socio-economic externalities, whereas depletion methods assess the diminishing opportunities for future generations linked to the global depletion of geological reserves. Therefore, it may be necessary to normalize impact scores measured with different impact methods consistently by using a common reference system such as a country, the world, or an industrial sector (Hauschild et al., 2018, p. 189). This normalization step is optional according to ISO 14040/14044 (ISO, 2006a, 2006b). It would allow relating different impact potentials to a common scale expressed in common

units and providing an impression of which impact potentials are rather large, and which are rather small (Hauschild et al., 2018, p. 189). Following the normalization step, further weighting between the impact scores from different methods could be done by taking into account the relative importance of impact pathways for different cultural perspectives (Chapter 2).

Moreover, it was discussed in Chapter 2 that the value of different mineral resources may vary based on the cultural perspectives, since they pursue different socio-economic objectives. For example, egalitarians may prioritize an equitable accessibility to mineral resources required to answer basic needs such as aggregates for construction, whereas individualists may prioritize their own accessibility to technology metals required for high technologies. The evaluation of the value of different mineral resources could thus aim to fit cultural perspectives.

Finally, impact pathways addressing economic externalities of product systems, e.g. surplus costs linked with future externalities as measured with the SCP method (Vieira et al., 2016) or insufficient reinvestment of rents earned from primary production as measured with the LIME2 method (Itsubo and Inaba, 2012), should also be based on coherent modelling choices with regards to the evaluation of e.g. reserve size and economic damage evaluation schemes.

7.4.2.2 Development of new methods: regionalization and socio-economic objectives

As discussed in Chapter 2, the regional distinctions between current development states and related socio-economic objectives underline the potential importance of a regionalized approach to impact assessment in the AoP natural resources. Looking at the global scope single-handedly is very likely to bypass potential injustices that may well be considered as an impact for at least parts of the human population. A simple theoretical example can be given to illustrate this: if all of the extracted mineral resources were to be transformed within a single country, generating a very large amount of economic value locally, other countries would be left with shrinking economic activities and handicapped purchasing power. Under such a scenario, the potential to make use of the economic value of mineral resources would be wholly used by humans *under the global scope*; however being detrimental to all countries but one *under the regional scope*. Indeed, the potential to make use of the value of mineral resources depends on their accessibility, itself depending on concerted human activities rather than geological availability, i.e. on the planning of mineral resource supply through exploration and technology development (Ali et al., 2017; Drielsma et al., 2016). As shown in Chapter 2, the value they generate for specific human groups depend on the structure of global supply chains. These structures may be modulated by the power and lobbying of dominant extractive industries, commercial alliances, embargos, etc., and as such, are definitely not strictly determined by environmental factors. In consequence, value judgements may be needed to assess the impacts linked with regional socio-

economic value creation and income redistribution. It may thus be desirable to assess the interregional equity in accessing the economic value of resource transformation activities in LCA.

In addition, the value generated along supply chains may also be assessed, i.e., in order to optimize the value that humans generate from a limited number of resources. The idea is that even when used efficiently, or in a non-dissipative way, mineral resources may be poorly used in terms of generating value for humans. As a theoretical -and absurd- example, 1 kilogram of gold could be transformed in a single cube and stored in a closet; as such, the use value generated for humans would be close to null for as long as the kilogram of gold remains there. Similarly, the transformation of gold in cubes would likely generate only small economic value along the supply chain. Thus, evaluating the value creation along supply chains and the value of products for humans could allow distinguishing between supply chains and products generating more or less value for humans. Again, the regional socio-economic objectives should be taken into account.

Impact pathways discussed in this sub-section and corresponding LCIA methods are yet to be established in LCA. As discussed in Chapter 2, assessing such impacts is not straightforward under the current LCA structure. Some innovative method developments could aim to bridge the gap between dissipation or depletion models with resource substitution and economic models; to establish regionalized distance-to-target objectives based on regional development (e.g., human development index); and to better characterize the use value of different metals in order to improve endpoint damage assessments.

7.4.2.3 *Connecting the AoP natural resources with ecosystem services*

Like mineral resources, ecosystems provide values to humans leading to their welfare (Dewulf et al., 2015). These values also occur over time, and are maintained for as long as ecosystems function properly (Rugani et al., 2019). Thus, the lost potential value due to mineral resource use could be assessed along with lost potential values provided by ecosystem services. Indeed, the degradation of ecosystems linked with production systems would decrease the value obtained from ecosystems in analogous way that ineffective mineral resource use reduces the potential value obtained from mineral resources. The impact assessment could attempt to integrate both value-related impact assessments altogether under a common AoP. Still, much efforts are needed to improve and harmonize endpoint assessments for single methods addressing different aspects of mineral resources and ecosystem services before considering to combine their impact scores into a single AoP.

7.5 Conclusion

There are multiple perspectives for the developments proposed in this thesis. The proposed conceptual framework to account for multiple impact pathways under the AoP natural resources may allow for a more exhaustive impact assessment under the AoP natural resources, and eventually, also help bridging the gap between values provided by resources in the economy, and those provided in ecosystems (i.e., ecosystem services). The next steps would be to harmonize LCIA methods for each of the eleven identified impact pathways under given cultural perspectives, and to weight their relative contributions to total impacts on the AoP. However, important method developments, as well as harmonization, normalization and weighting between existing methods will be needed for an exhaustive impact assessment of different aspects of mineral resource use to become viable.

The developed CFs for the ADR and LPST methods could be used by LCA practitioners wanting to assess the impacts of dissipation of mineral resources, given that the methods cover most metallic elements and that their CFs can be extended to more substances and updated thanks to the underlying machine-readable dataset and Python model made accessible online. The application of the proposed methods to more studies may reveal modelling flaws and help identifying further enhancements that could be implemented in the future. The appropriation of dissipation-oriented concepts and LCIA results by the LCA community, as well as their contribution to the decision-making process of LCA studies, will be an important step forward in terms of pursuing a more sustainable management of mineral resources through the use of the LCA methodology.

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Annex A

This annex presents the supporting information to Chapter 2, published as the supplementary information to “Charpentier Poncelet, A., Beylot, A., Loubet, P., Laratte, B., Muller, S., Villeneuve, J., Sonnemann, G., 2021. Linkage of impact pathways to cultural perspectives to account for multiple aspects of mineral resource use in life cycle assessment. *Resour. Conserv. Recycl.* 176, 105912. <https://doi.org/10.1016/j.resconrec.2021.105912>”.

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A.1 Identification of mineral resources to be safeguarded in the area of protection Natural resources

Using a clear definition of resources and of the functions they have for humans is necessary to develop a proper modelling concept for a life cycle impact assessment (LCIA) method (Drielsma et al., 2016; Schulze et al., 2020a). Yet, the terms “function”, “functionality”, “utility”, “role”, “(instrumental) value” and “service” have been associated to the term “resources” and used more or less interchangeably in the LCA literature (see e.g. Ardente et al., 2019; Berger et al., 2020; Dewulf et al., 2015; Frischknecht and Jolliet, 2019; Schulze et al., 2020). It is thus relevant to attempt to sort through these terms and establish a more intelligible terminology, building on the literature in the life cycle assessment (LCA) field and beyond. We first propose a clear identification of natural resources to be taken into account in the area of protection (AoP) natural resources, before switching the focus to mineral resources in particular.

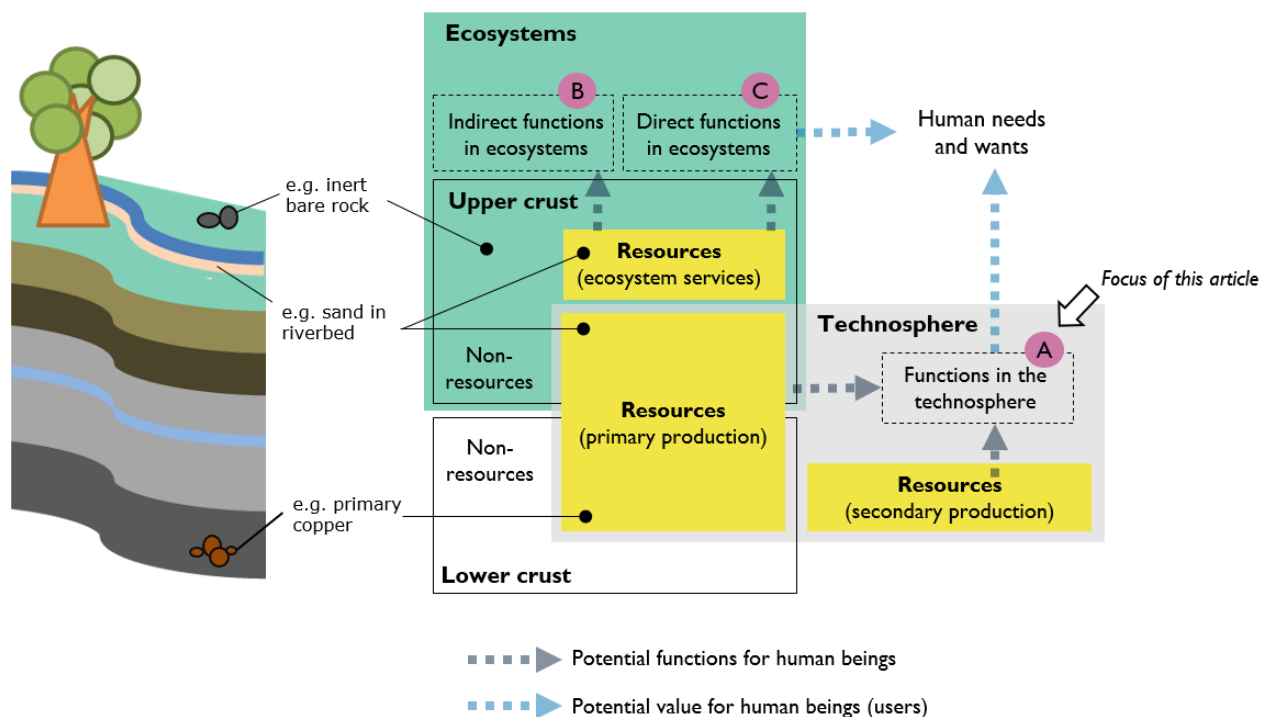


Figure A--1 (copy of Figure 2-1 of Chapter 2). Resources and their functions as part of the technosphere (A) and ecosystems (B and C). The indirect ecosystem functions (B) and direct ecosystem functions (C) are provided by systems of natural resources interacting together, i.e. ecosystems. The functions in the technosphere (A) are obtained through transformation activities in the economy.

A natural asset can be considered as a *resource* for as long as it may have a function for humans at some point in time (Frischknecht and Jolliet, 2016; Sonderegger et al., 2017). The functions that are *directly experienced* by humans may lead to human welfare, i.e. functions A and C depicted in Figure

A--1. For example, drinking water answers a vital nutrition need, while wood and minerals may be used as building materials providing shelter. *Direct functions* are also obtained from an in-situ interaction with ecosystems (e.g. contemplation of an aesthetic landscape) and are often considered as ecosystem services. Other indirect ecosystem services consist in various supporting functions which enable humans to obtain direct function from ecosystems (e.g. the water filtration service of sand, providing clean water) (Haines-Young and Potschin, 2018; Millennium Ecosystem Assessment, 2005). Like ecosystems, whose services or functions may be valued by humans, the transformation of resources in supply chains also provide products whose functions answer a variety of needs and wants leading to human welfare (Dewulf et al., 2015).

We hereon focus on mineral resources. The only potential function of mineral resources found in the lower crust (designating the part of the Earth's mantle which does not interact with the ecosystems) is obtained through their potential functions in the economy (A in Figure A--1). These mineral resources are principally the metal content of metal ores, and are estimated not contribute to ecosystem functions and services. Mineral resources part of the upper crust (superficial earth layer), such as sand and gravel, may also have in-situ functions in the ecosystems in which they are found (Frischknecht and Büsser Knöpfel, 2013; Schulze et al., 2020a). For instance, mineral resources may contribute to cultural, recreational or spiritual functions as part of natural sceneries (C in Figure A--1) (Dewulf et al., 2015). They may also contribute to other direct and indirect functions provided by ecosystems (e.g. water filtration). These are represented by B in Figure A--1). Functions B and C may contribute to human welfare, though they are seldom traded on markets.

Concerning mineral resources to be safeguarded within the AoP natural resources, it is their potential value in the technosphere which is of interest (Berger et al., 2020), i.e. those represented in box A. They include both surface (e.g. sand used for glassmaking) or sub-soil (e.g. chalcopryrite extracted for its copper content) mineral resources that may be used in the economy. In Chapter 2, we focus specifically on these mineral resources.

A.2 Geographical and temporal variability in the accessibility to resources

Time horizons have been discussed extensively in the LCA community, for example by Steen (2006). The outputs of the SUPRIM project suggest that the problem with mineral resources is related to their accessibility at the global scale over short (0-25 years) or long (>100 years) timeframes (Schulze et al., 2020b; SUPRIM, 2019). As a justification to consider the global scope, the authors mention that metals are generally traded on international markets. Occupation, hibernation and environmental dissipation are deemed to be potentially detrimental to resource accessibility on the short term, while only environmental dissipation is considered to be problematic in the long term (van Oers et al., 2020). The

authors suggest that only flows of resources to the environment could be considered to be dissipative in the long term, following the assumption that resources that remain in anthropogenic stocks such as final waste deposits and tailings will be accessible in the long run. Moreover, the authors highlight that multiple factors may influence the accessibility to resources, such as the concentration of a target metal in a geological or anthropogenic stock, as well as technical, economical and legal factors (Schulze et al., 2020b). Contrastingly, the Joint Research Centre suggests to account for dissipation in the short term, based on the notion that any flow of resources to the environment, final waste disposal facilities and products in use in the technosphere (with low-functional recovery) may be reported as inaccessible (i.e. dissipative) within a time horizon of 25 years (Beylot et al., 2020a). They also suggest a *“hypothetical and simplified scenario”* for the very long term in which only flows to the environment are considered to be dissipated, alike the SUPRIM approach.

Yet, the LCA community has paid scant attention at identifying the possible diversity of means to access (i.e. extract) and use (i.e. occupy) resources amongst one same human generation, as well as the different sets of values that are targeted by different human groups. It is apparent that organisational and regional specificities may also play an important role in determining whom of the current generation, and potentially of future ones, has access to the value of resources. Indeed, resources are not distributed (or concentrated) evenly throughout the planet, and different nations and organisations have different economic and technical means to operate worldwide. Moreover, the same businesses may operate within multiple regions that each have their own laws and policies. In turn, economic activities allow citizens to consume goods with the revenues they earn from work, investments, national income redistribution, etc. (cf. section 2.2.2 of Chapter 2).

Hence, given:

1. the globalized state of value chains (The World Bank, 2020);
2. the discrepancies in between country development, domestic resource consumption and the associated economic activities of each nation (Graedel and Cao, 2010; The World Bank, 2020; UNEP, 2017, 2016);
3. and the potential supply risks for regions (or organisations) associated to environmental, social, governance, regulatory and geopolitical aspects (Ali et al., 2017; Lèbre et al., 2020, 2019; Sonnemann et al., 2015);

it is apparent that the accessibility to mineral resources varies significantly in between regions.

We here attempt to systematically identify the geographical and temporal aspects that might influence the accessibility to resources, based on a literature survey. This initial identification provides additional insights on which human activities and pathways can be relevant to address when assessing the

impacts of mineral resource use on the AoP natural resources following different cultural perspectives. For the comprehensibility of this analysis, the main steps of global value chains are aggregated and analysed as presented in Figure A-2.

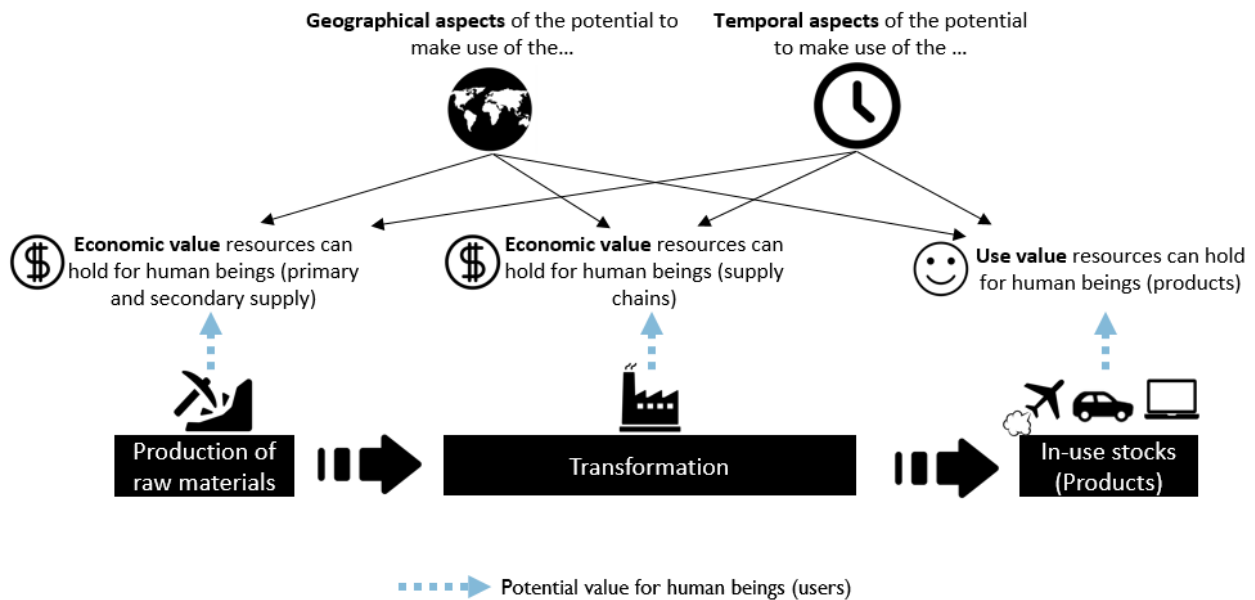


Figure A-2. Aggregated steps of global value chains considered for the analysis of the geographical and temporal aspects influencing the potential to make use of the value of resources, i.e. through accessing resources at some point in space and time

A.2.1 Geographical aspects

Parts of the two following paragraphs originate from section 2.2.2 of Chapter 2. The economic value of primary resources (natural capital) may be accessible to those that can legally operate locally or abroad while having the indispensable pre-accumulated capitals to do so. These include the financial capital to invest in new projects (e.g. exploration and building new infrastructure), the manufacturing capital required for extraction and transformation, the human capital in the form of knowledge and skills (e.g. breveted metallurgical process and trained personnel), and the social capital (including favourable geopolitical relationships and the social license to operate locally). Developed nations and organisations within, that can rely on extensive pre-accumulated capitals, are likely to be more competitive and thus to have a privileged access to resources. This generally holds true for the economic value of extracted resources, as well as for the subsequent benefits of their transformation into higher value-added semi-products and products. Similarly, the use value of products is accessible to consumers that have the means to purchase them. These are more generally associated to citizens of developed countries rather than developing ones (UNEP, 2016).

Moreover, local environmental, social and governance (ESG) risks may have an incidence on which resources are accessible in different regions, as such risks can affect the willingness to explore for ore bodies in different regions and the feasibility of subsequent mining operations (Ali et al., 2017; Kerr, 2014; Lèbre et al., 2019; Northey et al., 2018). An increasing awareness of labour rights (ILO, 1988) and for a more responsible sourcing of minerals (e.g. “conflict-free” minerals, see e.g. Young (2018)) may diminish the feasibility of certain mining operations where mining results from unjust working conditions. Conversely, national policies and development schemes may go counter current of ESG risks by promoting a more intensive exploitation of the domestic natural capital, or by securing the provisioning of resources through various strategies such as trade agreements and stockpiling. Nations and organisations may attempt to secure their access to resources in order to sustain their economic activities, which is central to criticality methods (Graedel et al., 2012) and supply risks methods (Bach et al., 2018; Gemechu et al., 2016). The latter methods evaluate the outside-in provisioning risks for a given nation or supply chain (Berger et al., 2020; Sonderegger et al., 2020), which may support decision-making when setting-up strategies to secure resource provisioning over time. However, ESG risks have not been considered in the computation of supply risk, which may prove to be a limitation of these methods (Lèbre et al., 2019).

A.2.2 Temporal aspects

All of the geographical aspects identified above may evolve over time. Aside from those, the accessibility geological stocks may be affected by cumulative extraction leading to depletion (van Oers et al., 2019, 2002). The efforts required to access resources in the future may also increase due to the decreasing quality of the remaining ores (Verones et al., 2017). These changes over time may induce additional efforts and the associated costs required to provision more resources (Vieira et al., 2016). Conversely, intensified exploration and shifts in technology may lead to an increased mining efficiency and an overall increase of the accessibility to mineral resources (Ericsson et al., 2019). Similarly, the development of new technologies could allow to access some resources stored in tailings and landfills (Ayres et al., 2002; Falagán et al., 2017; Sapsford et al., 2017; Winterstetter et al., 2015). However, it is not possible to predict nor the discovery of new deposits (possibly of high grade quality), nor the investments in exploration and/or in technological developments that could secure additional supply over time with certainty. Resource pessimists tend to view future supply risks resulting from the depletion of finite stocks, while optimists tend to view technology and investment as the mitigating solution to overcome the eventual supply risks of exhaustible resources (Tilton, 1996). Efforts spent on targeting an increased global sustainability may also influence the total quantity of resources made accessible to different users over time. For example, (Watari et al., 2020) showed the necessity to drastically reduce metal consumption per capita in middle and high income countries to pursue the

environmental target of 2 °C of global warming by 2100, while UNEP is pushing towards a decoupling between economic growth, well-being and resource consumption (IRP, 2014; UNEP, 2017, 2011). Accordingly, resource management strategies may vary between different cultural viewpoints, as discussed in Chapter 2.

A.2.3 Development scenarios and cultural perspectives

A brief description of the GEO-4 scenarios is proposed below. The detailed description of each scenario can be obtained from the chapter 9 of the report by UN's Environmental Programme (UNEP, 2007).

- The Markets First scenario describes a world in which international trade is deregulated and decisions are mostly meant to favor a flourishing global economy. The private sector is relatively powerful in comparison to the government and civil sector. Investments in technology allow to adapt to a changing environment (UNEP, 2007).
- The Sustainability First scenario describes a world where all actors from all sectors and at all scales (individuals, public and private organizations, governments) cooperate to address social and environmental concerns at the international scale. International markets are increasingly open, with a strong embodiment of fair trade principles (UNEP, 2007). As noted by Elshkaki et al. (2018) about their resembling “Equitability World” scenario, actors act to support UNEP's Sustainable Development Goals and to deliver economic, social and environmental advances to all in an equitable manner.
- The Policy First scenario describes a world where goals that are similar to the Sustainability First scenario are pursued, albeit being driven by highly centralized policy rather than an integrated transversal and vertical cooperation between actors. It aims to balance long-term economic development with the environmental and social externalities of production and consumption patterns. For instance, it recognizes the limitations of free markets to balance profit making with its externalities on ecosystem services and to ensure the stewardship of non-renewable resources. Hence, international markets become increasingly open however with some embodiment of fair trade principles (UNEP, 2007). Moreover, governments play an increasingly important role in redistributing global income, especially towards education and health. As noted by Elshkaki et al. (2018) about their resembling “Towards resilience” scenario, a strong emphasis may be put on global environmental challenges such as global warming through an intensive transition to renewable energy.
- The Security First scenario describes a world in which nations prioritize their security (e.g. through large investments in the military sector) and economy. National economies move

towards protectionism, with less international trade, and focus on securing their access to natural resource assets (UNEP, 2007).

As indicated in section A.2, the geographical variability in the accessibility in resources can evolve over time. Therefore, linking these scenarios with cultural perspectives enables to draft general resource management strategies starting from the current situation of the accessibility to resources (section 2.2.2 of Chapter 2) and allowing to pursue given socio-economic objectives. These developments are proposed in section 3 of Chapter 2, and are estimated to be plausible in terms of the accessibility of resources for different users and use of mineral resource use over time under the different cultural perspectives. We emphasize that the analysis is not intended to provide a detailed analysis of local micro-changes and feedback mechanisms between actors, but only highlight probable global trends for developed and developing countries in comparison with the current situation. The proposed theorization throughout Chapter 2 is estimated to be in accordance with the scope of interest respective of each cultural perspective in terms of (1) resource-based welfare, (2) geographical extent and (3) temporal extent indicated in Figure A-3.

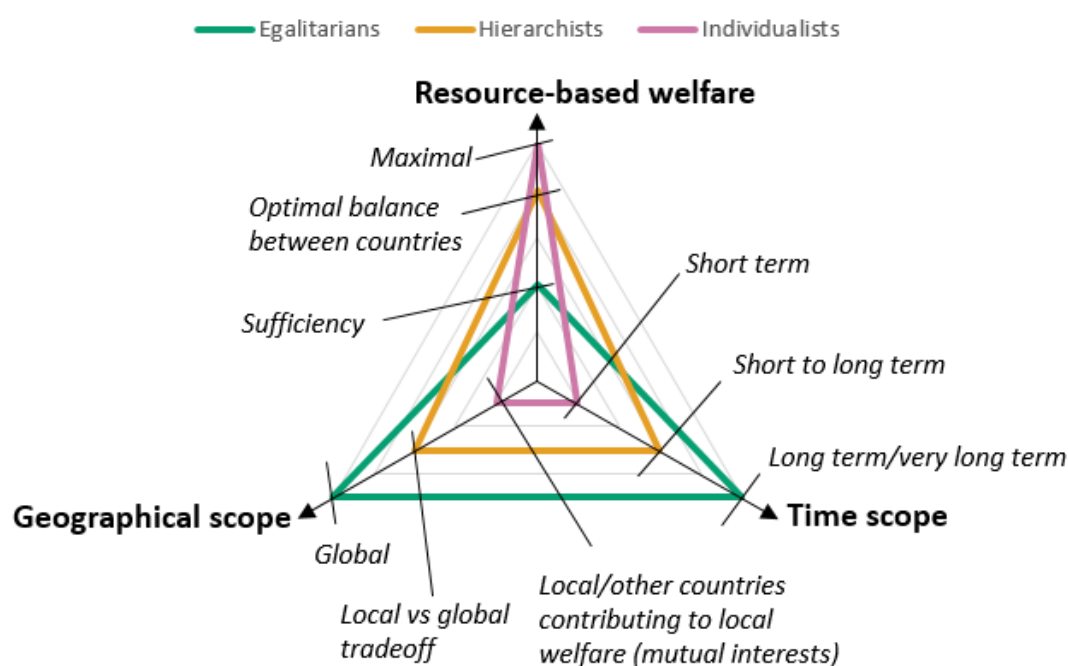


Figure A-3. Relative importance of resource-based welfare over time and space for three cultural perspectives. The three axes' scales are only indicative to compare between the three perspectives and do not refer to any concrete metrics.

When analyzing differences between the three perspectives, one may associate individualists most closely with techno-centric individuals (short-term local welfare through man-made environment; the natural and man-made capitals are entirely exchangeable), egalitarians with eco-centric individuals (long-term global welfare through the preservation of nature and resources; the so-called “critical natural capital” is irreplaceable) and hierarchists as some middle ground between both. As different values and priorities are given to the man-made environment (resource-based welfare) and to ecosystem services (ecosystem-based welfare) under different perspectives, it would be necessary to assess the impacts of resource use altogether with those on ecosystem services in order to represent all of the potential values obtained from the environment holistically under different cultural perspectives.

Figure A-4 depicts projected trends in future mineral resource consumption amongst developed and developing countries according to objectives for each of the three cultural perspectives. The depicted curves are merely indicative in order to compare between the three perspectives and do not refer to any concrete metrics.

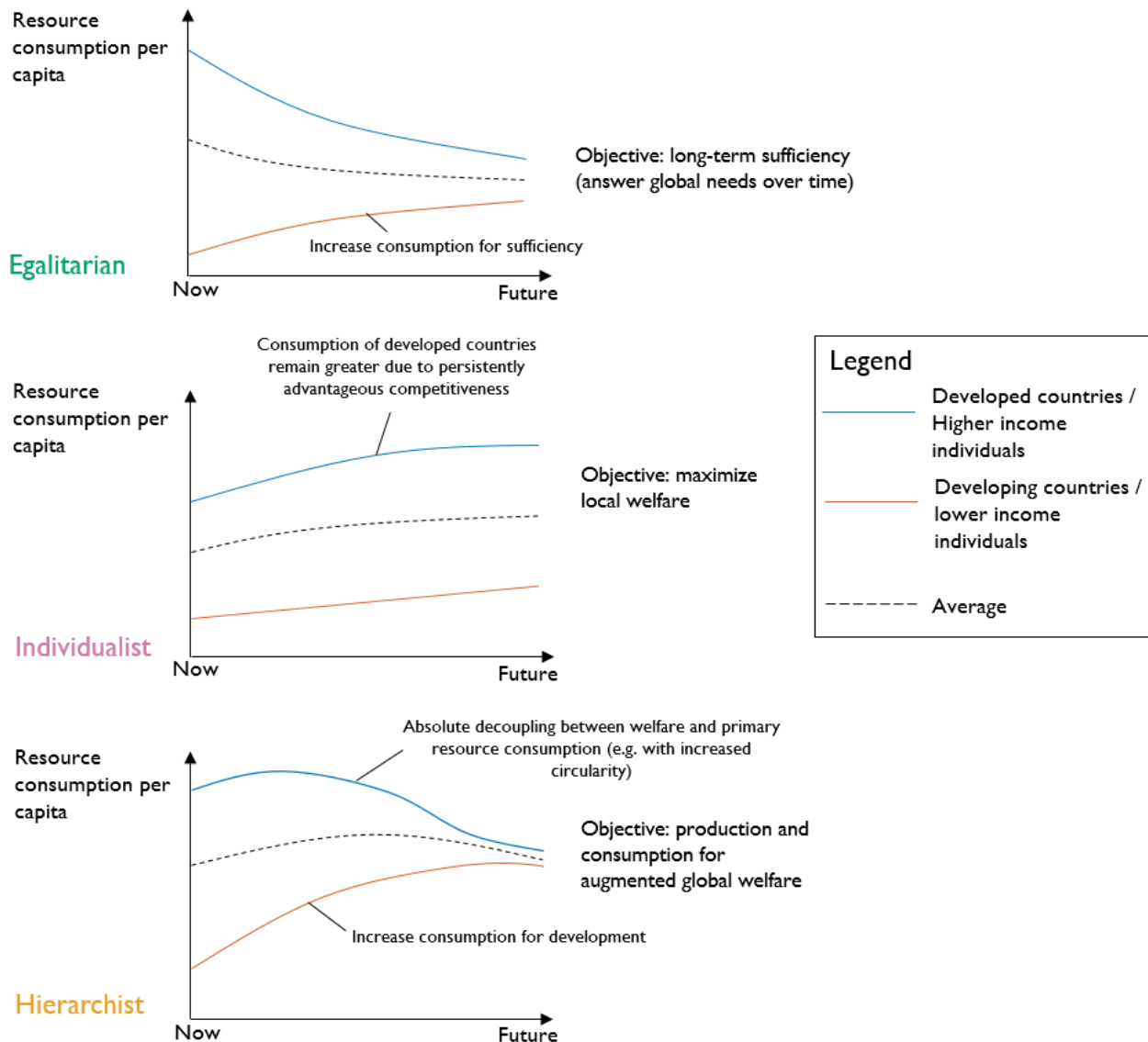


Figure A-4. Potential evolution of resource consumption over time in developed and developing countries depending on the adopted cultural perspective in global resource management. In the depiction, the initial split between developed and developing countries is assumed to remain the same although developing countries may indeed become developed at some point in the future.

The hierarchist' and individualist' curves are roughly inspired from the future scenarios of resource consumption developed by the International Resource Panel (IRP). The individualist' curves are based on the pursuit of historical trends, considering a business as usual model, and the hierarchist' curves are based on the Towards sustainability model, considering the pursuit of SDGs (IRP, 2019, chapter 4.5).

A.3 Justifications for resource management strategies estimated to be proper to cultural perspectives

One could imagine a continuum between an extreme eco-centric perspective, where critical natural capital is even more important to preserve than some human lives of the current generation, to extremely self-centered (individualist) anthropocentric viewpoints, where ecosystems are considered as valueless as soon as they are not providing the self-centered group with any value, putting in danger other humans that depend on these ecosystems to answer their basic needs. Such extreme perspectives were not considered to be useful in the context of our study nor to orientate decision-making in LCA. Indeed, one can expect that extremist regimes would realistically not bother with the use of LCA to improve their decision-making at the political or organizational level, as LCA studies (i.e. improving the profile of production/consumption systems) do not align with their motivations. For example, very strong sustainability has been called absurd and deemed impractical by some authors (Ekins et al., 2003).

In Chapter 2, we instead aimed to consider a range of moderate viewpoints that generally at least respect human rights and that that could be fairly reasonably endorsed for policy-making in democratic nations comprised of representative shares of each cultural perspectives. It is also one of the reasons we decided to rely on plausible development scenarios as defined by UNEP. Indeed, according to the Cultural Theory, a population will inevitably composed of multiple groups of humans from each cultural perspectives at any time (though single beings may switch from one another over time). We therefore considered that more relevant (and moderate) viewpoints oscillated between strong sustainability focused on the preservation of nature (for egalitarians) to more typical individualist market-oriented regimes.

For transparency, we further discuss our assumptions underlying the linkage between resource management strategies and cultural perspectives below. These positions could of course be debated. We here remind that the focus of Chapter 2 is solely on the use of mineral resources in the economy, and not on the protection of ecosystem services or critical natural capital. The latter should also be considered for an exhaustive assessment of values obtained from the environment. On similar topics of discussion, we refer readers to other literature on weak and strong sustainability (Bullock, 2017; Ekins et al., 2003; Neumayer, 2013; Pelenc and Ballet, 2015), different takes on sustainability as discussed by e.g. Norton (1992) and Schaubroeck and Rugani (2017), and various policy-oriented documents analyzing the historical, present and future trends of resource consumption, resource productivity and welfare (UNEP, 2019, 2017, 2016).

A.3.1 Egalitarians

We estimated that the protection of nature through limited consumption for the current generation, i.e. aiming for sufficiency rather than welfare, was most in line with egalitarian's view of the world. We considered that egalitarians (1) would generally attempt to protect ecosystem services as an important source of natural resources/ of a necessary support to human life and welfare over time, and (2) would minimize our reliance on mineral resources as a means to secure current human welfare. In this way, future generations may (1) have access to similar ecosystem services as we enjoy today, and (2) to sufficient amounts of mineral resources to answer their needs over time. Complementarily, the conception (or "myth") of nature relevant to each cultural perspective can justify their relation to the environment and the way they exploit it. The proposed rationale for egalitarians is reinforced by their myth of nature, i.e., *nature is fragile*, and their aversion to risk-taking (Hofstetter, 1998; Mamadouh, 1999). Similarly, the Safe and Just Space, as referred to by Neill et al. (2018), is said to align on strong sustainability principles; the authors conclude that "provisioning systems must be fundamentally restructured to enable basic needs to be met at a much lower level of resource use". The evolution of resource consumption under such a view of resource management is depicted in Figure A-4.

A.3.2 Individualists

As noted in Chapter 2, the individualist perspective "is inherently hardly compatible with global assessments as the interests of each subgroup are self-centered and primarily valued over that of others". While some could support that the liberal pursuit of self-centered interests lead to a greater global welfare, we would not agree this to be true especially when it comes to crossing national boundaries. Thus, we rather thought of "global individualism" as the sum of nations each attempting to generate as much local welfare following their own interests: perhaps, e.g., by aiming to increase current Gross Domestic Product (GDP) at all cost, even if potentially detrimental to other nations and/or future generations. As noted in Chapter 2, the individualist take on resource use seems to be predominant currently. This business as usual paradigm tends to benefit more to high-income countries, businesses or individuals than others due to their advantageous competitiveness. It can be expected that globally, individualistic populations would generate a decent amount of resource-based value, but that this value would not be redistributed evenly. Hence, global equity in accessing resource-based welfare is estimated to be lower for individualists: if a few select powerful countries act individualistic in a Security first scenario-related manner, global equity is lower; if a few select powerful countries act individualistic in an open global market-oriented manner, than it can be expected that more value is generated, yet remains most concentrated in these same few countries (cf. Figure 2-2 of Chapter 2).

In Chapter 2, we argue that individualists currently favor a high resource consumption economy with overall small incentives to reduce waste or increase circularity unless economically profitable, as to maximize local resource-based welfare. Indeed, considering the heavy consumption of resources in high-income countries, which were broadly associated to an individualist perspective (cf. sections 2.2.2 and 2.3.2 of Chapter 2), such view of resources seems to be predominant amongst individualists for the time being. The context is important to take into account, as it could hypothetically change in the future: a shift of perception could result from an observed (scientifically established) scarcity of resources, leading to individualists believing and acting upon the said scarcity of resources. Criticality assessments may embody the emergence of such viewpoints. Still, currently, at the organizational or national scale, high resource consumption allows for a stronger economic profile and related power/competitiveness that fulfills self-centered interests. Moreover, individualists believe in a *nature benign* myth of nature that can take experimentation, trial and error (Hofstetter, 1998; Mamadouh, 1999): under such a conception, human groups can gather large amounts of resources from the environment for themselves without worrying too much about its consequences, including in terms of future scarcity, or scarcity for other users.

Regarding the local scope of LCA studies that are most proper to the individualist perspective, we would imagine a local assessment ranging from the organizational scale up to groups of nations/countries sharing common interests. Considering that, local would refer to e.g. organizational, national or commercial zones (e.g. European Union) scales. Then, the individualist assessment could focus on the impacts of resource use and the welfare generated in the organization or territory while disregarding the rest.

A.3.3 Hierarchists

We considered that a science-based resource management strategy aiming for socio-economic development would appeal to hierarchists, i.e. increasing welfare rather than prioritizing an egalitarian satisfaction of basic needs through sufficiency. The hierarchist myth of nature is that nature is perverse/tolerant to some extent, meaning that it is robust, but can only undertake so much while remaining in a safe zone, beyond which things go wrong (Mamadouh, 1999). According to Mamadouh, this myth justifies the power given to experts to evaluate the safety zone under the hierarchist perspective. Under such view of the world, the overall increasing welfare is partly generated at the expense of the environment, i.e., by substituting the value of natural capital with that of other capitals, aligning on weak sustainability principles.

A.4 Analytical grid for the classification of impact pathways to cultural perspectives

We used the grid presented in Table A1 to assess impact pathways' relevance to egalitarians, individualists and hierarchists. Three criteria are evaluated for each impact pathway: regional focus, temporal focus and relevance of the suggested resource management strategy (i.e. implicit specific objective/safeguard subject) to pursue cultural socio-economic objectives (**Perspectives**: E = egalitarian, I = individualist, H = hierarchist. **Relevance**: - = none to very low, + = low, ++ = medium, +++ = high). We provide additional justifications and details in parentheses where most relevant. In section 2.5 of Chapter 2, the “most relevant pathways” are those evaluated with “+” or higher. Impact pathways that are evaluated with a “-” for at least one criteria were considered not to be most relevant for that cultural perspective.

Table A1. Evaluation of eleven impact pathways regarding three criteria for egalitarians, individualists and hierarchists, and assessment of total relevance.

| # impact pathway | Description (adapted from Berger et al., 2020) | Regional focus | Relevance of regional focus | | | Temporal focus | Relevance of temporal focus | | | Implicit beliefs (e.g. regarding capacity of future generations to adapt) & appropriate response (<i>preferred resource management strategy implicit to pathway</i>) | Relevance of beliefs & strategy to attain socio-economic objectives | | | Relevance of impact pathway to cultural perspective | | |
|------------------|---|------------------------------------|-----------------------------|----------------|---------|--|-----------------------------|---|---------|--|---|---|---|---|---|----------|
| | | | E | I | H | | E | I | H | | E | I | H | E | I | H |
| 1 | Depletion reduces the accessibility of resources for future generations, resulting in a lost potential for future generations to make use of the value of geological stocks | Global | ++ + | + | ++ + | Long term | ++ + | + | + | Mineral resources prone to exhaustion: Prevention of extraction to retain resources for future generations | +++ (risk adverse) | + | + | ++ + | + | + |
| 2 | Current over-extraction of geological resources leads to lower economic rent over time, resulting in a lost potential to make use of the economic value of resources | Global (assessment could be local) | ++ + | +++ (if local) | ++ + | Mid to long term (impact assessment could adapt) | ++ + | + | ++ + | Economic value of mineral resources should be preserved for future generations: Prevent over-consumption by current generation | + | + | + | ++ +/ | + | ++ +/ |

| # impact pathway | Description (adapted from Berger et al., 2020) | Regional focus | Relevance of regional focus | | | Temporal focus | Relevance of temporal focus | | | Implicit beliefs (e.g. regarding capacity of future generations to adapt) & appropriate response (preferred resource management strategy implicit to pathway) | Relevance of beliefs & strategy to attain socio-economic objectives | | | Relevance of impact pathway to cultural perspective | | |
|------------------|---|------------------------------------|-----------------------------|-------------------------|----|---|-----------------------------|---|----|--|---|---|------|---|-------------------------------------|------|
| | | | E | I | H | | E | I | H | | E | I | H | E | I | H |
| 3 | Current extraction leads to diminishing ore grades and increasing costs, resulting in a reduced potential to make use of the economic value of geological stocks | Global | ++ | · | ++ | Mid to long term (short-term effects are more vague) | ++ | · | ++ | Efforts increase for future generations: Reduce extraction to retain economic surplus value for future generations | + | - (optimism for technical progress) | + | ++ | · | ++ |
| 4 | Insufficient re-investments of economic rent of resources, resulting in a lost potential of future generations to make use of the economic value of resources | Global (assessment could be local) | ++ | +++ (if local) | ++ | Mid to long term | ++ | · | ++ | Current income discounts cost of depletion for future generations: increase reinvestment to reduce future user cost (i.e. to preserve economic value for future generations, even if resource is depleted) | X/+ (for egalitarians, economic value/capital does not substitute other capitals) | · | +/++ | -/+ | · | +/++ |
| 5 | Mid-term supply risk due to physico-economic scarcity may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic value and use values of resources | Global | ++ | + (if assumed relevant) | ++ | Short to mid-term: "a few decades" according to MR taskforce (Sonderger et al., 2020) | · | + | ++ | Mineral resources are needed in the economy but prone to physico-economic scarcity: Reduce reliance on physico-economically scarcest resources | + | + (optimist in human capacity to discover more) | +++ | · | + (if global scope deemed relevant) | +++ |

| # impact pathway | Description (adapted from Berger et al., 2020) | Regional focus | Relevance of regional focus | | | Temporal focus | Relevance of temporal focus | | | Implicit beliefs (e.g. regarding capacity of future generations to adapt) & appropriate response (<i>preferred resource management strategy implicit to pathway</i>) | Relevance of beliefs & strategy to attain socio-economic objectives | | | Relevance of impact pathway to cultural perspective | | |
|------------------|--|------------------------------------|-----------------------------|------------------------------|----|--|-----------------------------|------------------|--------------------------|--|---|---|-----|---|--|-----|
| | | | E | I | H | | E | I | H | | E | I | H | E | I | H |
| 6 | Dissipation (as well as hoarded and abandoned resources; cf. Dewulf et al., 2021) leads to the inaccessibility of resources, resulting in a lost potential to make use of the economic value and use values of resources | Global (assessment could be local) | ++ | +++ (local) - (global) to | ++ | Short to long term (impact assessment could adapt) | +++ (long term) | +++ (short term) | +++ (short to long term) | Dissipated resources cannot be replaced: Conserve in the economy in a more efficient (circular) way | + / ++ (focus on reduction rather than optimization) | - / + (for those with higher supply risk) | +++ | + / ++ | + / ++ (may be relevant within supply risk assessment) | +++ |
| 7 | Supply risk may generate an inaccessibility to resources (supply disruption), resulting in a lost potential to make use of the economic values of resources (also use values at regional or national scale) | Organizational/ National | + | +++ | + | Short term | + | +++ | + | Supply risk should be avoided to ensure that organization/nation remains competitive and generate resource-based welfare: Secure access to (important) resources | + | +++ | + | + | +++ | + |

| # impact pathway | Description (adapted from Berger et al., 2020) | Regional focus | Relevance of regional focus | | | Temporal focus | Relevance of temporal focus | | | Implicit beliefs (e.g. regarding capacity of future generations to adapt) & appropriate response (preferred resource management strategy implicit to pathway) | Relevance of beliefs & strategy to attain socio-economic objectives | | | Relevance of impact pathway to cultural perspective | | |
|------------------|--|--|-----------------------------|-----------------------------------|--------------|--|-----------------------------|------------------|-------------------------|--|---|----|--------|---|-----------|-----------|
| | | | E | I | H | | E | I | H | | E | I | H | E | I | H |
| 8 | Unsustainable distribution of resources affects non-adapted or non-competitive users, resulting in a lost potential to make use of the economic value of resources | Global | ++ | . | ++ | Short to long term (impact assessment could adapt) | ++ | +++ (short term) | ++ | Resources should be distributed equitably/efficiently to pursue relevant socio-economic objectives (strategies depend on specific objectives for cultural perspective) | + / ++ (current distribution may lead to long-term effects, e.g. country development) | . | ++ | ++ | . | ++ |
| 9 | Inefficient creation of economic value in supply chains making use of resources, resulting in a lost potential to make use of the economic value of resources (assessment should take nation's development/ organization's context into account) | Relevant to assessment. I : local E, H: Global | +++ (global) | ++ (national), +++ (organization) | +++ (global) | Short term | + | +++ | + (focus on short-term) | Resources should be used efficiently to pursue relevant socio-economic objectives (strategies depend on specific objectives for cultural perspective) | - / + (focus on short term, and on economic value, not use value) | ++ | + / ++ | - / + | +++ / +++ | +++ / +++ |

| # impact pathway | Description (adapted from Berger et al., 2020) | Regional focus | Relevance of regional focus | | | Temporal focus | Relevance of temporal focus | | | Implicit beliefs (e.g. regarding capacity of future generations to adapt) & appropriate response (<i>preferred resource management strategy implicit to pathway</i>) | Relevance of beliefs & strategy to attain socio-economic objectives | | | Relevance of impact pathway to cultural perspective | | |
|------------------|---|--|-----------------------------|----|----|--|-----------------------------|---------------------------------|----|--|---|--|--|---|--|--------|
| | | | E | I | H | | E | I | H | | E | I | H | E | I | H |
| 10 | Unsustainable distribution of final products affects non-adapted or non-competitive users, resulting in a lost potential to make use of the use values of resources | Global | ++ | . | ++ | Short to midterm (depends on which products) (impact assessment could adapt) | + | ++/+++ (focus on short/midterm) | ++ | Final products should be distributed equitably to pursue relevant socio-economic objectives (strategies depend on specific objectives for cultural perspective) | +/++ (temporary short/midterm fix) | . | ++ (temporary short/midterm fix) | +/++ | . | ++ |
| 11 | Inefficient creation of use value with final products, resulting in a lost potential to make use of the use value of resources (assessment should take nation's development/context into account) | Relevant to assessment. I : local E, H: Global | ++ | ++ | ++ | Short to midterm (depends on which products) (impact assessment could adapt) | + | ++/+++ (focus on short/midterm) | ++ | Final products should be used efficiently to pursue relevant socio-economic objectives (strategies depend on specific objectives for cultural perspective) | ++/+++ (e.g. more use value and equitable distribution) | +/+++ (depends on nations' development states) | ++/+++ (focus is rather on short to midterm) | ++ (focus is rather on short to midterm) | +/+++ (may be more relevant for less competitive nations, that have less means to purchase products) | ++/+++ |

A.5 Description of selected LCIA methods discussed in section 2.4

Existing LCIA methods that could be used to address most of the impact pathways 1-7 identified in section 2.4 of Chapter 2 have already been suggested, interim recommended, or recommended by the MR taskforce to address different questions (table 1 of Berger et al., 2020). Complementarily, we also took newly developed methods that were not available to the MR taskforce into account. These mostly address resource dissipation, which represents the share of resources that have been made economically or technically inaccessible due to human activities (Beylot et al., 2020b). They include the environmental dissipation potential (EDP) method assessing the impacts of emissions to the environment (van Oers et al., 2020), the Joint Research Centre (JRC)'s suggested approach to account for dissipation at the inventory level (Beylot et al., 2021, 2020a), as well as the average dissipation rate (ADR) and lost potential service time (LPST) methods which estimate the impacts of global dissipative flows of metals (Charpentier Poncelet et al., 2021c). Finally, the Crustal scarcity indicator (Arvidsson et al., 2020) and the Future Welfare Loss method (Huppertz et al., 2019), were also considered.

The following descriptions provide a brief overview of each LCIA method referred to in Chapter 2. The descriptions for the abiotic depletion potential (ADP), Future welfare loss, LIME2 endpoint, surplus ore potential (SOP), surplus cost potential (SCP) ESSENZ, GeoPolRisk and Cumulative exergy extraction from the natural environment (CEENE) methods heavily rely on the works of the Life Cycle Initiative's Taskforce on mineral resources ("MR taskforce") (Berger et al., 2020; Sonderegger et al., 2020). For dissipation-oriented approaches, namely the environmental dissipation potential (EDP) method, the Joint Research Center (JRC) suggested approach, the average dissipation rate (ADR) and the lost potential service time (LPST) methods, the descriptions heavily rely on the book chapter of Charpentier Poncelet and colleagues (2021). For the Crustal scarcity indicator, the original article was consulted (Arvidsson et al., 2020). For a complete description of each method and of their formulas, the original papers or reports that are referenced for each of them should be consulted.

Abiotic depletion potential (ADP) ultimate reserves

The ADP ultimate reserves method (van Oers et al., 2019, 2002; van Oers and Guinée, 2016) is recommended by the MR taskforce to assess the contribution of a product system to the depletion of mineral resources. The characterization factors are obtained by dividing the annual production of mineral resources with the square of the ultimate reserves. The latter are estimated based on the crustal content of each element and are used as a proxy for the ultimately extractible reserves. The impacts are proposed as midpoint indicator.

ADP economic reserves

The ADP economic reserves method (van Oers et al., 2002; van Oers and Guinée, 2016) is suggested by the MR taskforce to assess potential availability issues for a product system related to mid-term physico-economic scarcity of mineral resources. The characterization factors are calculated alike those of the ADP ultimate reserves, but considering the currently extractable economic reserves rather than ultimate reserves.

Future welfare loss

The future welfare loss method (Huppertz et al., 2019) “assesses the potential externality of lost hypothetical rents due to current overconsumption of the resource” (Berger et al., 2020). The characterization factors allow to compare the socially optimal price of resources with their actual price (without extraction costs) to establish the social cost of current extraction.

LIME2 (Endpoint)

The LIME2 endpoint method (Itsubo and Inaba, 2012) is interim recommended by the MR taskforce to assess the (economic) externalities of mineral resource use. The method “assesses the share of the economic value of extracted resources that needs to be reinvested to maintain the benefit obtained from the extraction of resources” (Berger et al., 2020).

Surplus Ore Potential (SOP)

The SOP method (Vieira et al., 2017) is interim recommended by the MR taskforce to assess the consequences of a product system to the changing mineral resource quality. It is proposed as a midpoint method that measures the surplus amount of ore that will be required to extract in the future due to present extraction. The short term reserves are used to calculate the SOP for the individualist perspective, and the long term ultimate recoverable reserves are used for the hierarchist and egalitarian perspectives (Huijbregts et al., 2017; Vieira et al., 2017).

Surplus Cost Potential (SCP)

The SCP method (Vieira et al., 2016) is not currently recommended by the MR taskforce to assess the contribution of a product system to the depletion of mineral resources. However, it is described as we referred to this method in the section 2.4 of Chapter 2. SCP is proposed to measure endpoint damage on the area of protection natural resources. The endpoint damage is calculated similarly to the SOP, but using cumulative cost-tonnage relationships rather than cumulative grade-tonnage in order to generate the surplus cost potential (SCP) characterization factors (Huijbregts et al., 2017; Vieira et al., 2016).

ESSENZ

The ESSENZ method (Bach et al., 2019, 2016) is interim recommended by the MR taskforce to assess potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects. It quantifies eleven geopolitical and socioeconomic accessibility constraints, each of which are attributed an indicator using distance to target values. Above the defined target value, accessibility constraints are estimated to occur.

GeoPolRisk

The GeoPolRisk method (Cimprich et al., 2019, 2018; Gemechu et al., 2016) is suggested by the MR taskforce to assess potential accessibility issues for a product system related to short-term geopolitical and socio-economic aspects. It “weights the political stability of upstream raw material producing countries by their import shares to downstream product manufacturing countries” (Berger et al., 2020).

Cumulative exergy extraction from the natural environment (CEENE)

The CEENE method (Dewulf et al., 2007) is interim recommended by the MR taskforce to assess the impacts of mineral resource use based on thermodynamics. It assesses the amount of additional exergy extracted from resources (e.g. copper contained in chalcopyrite) in comparison to a defined reference compound in the natural environment (e.g. copper contained in seawater) (Berger et al., 2020).

It was not included in Table 2-2, Figure 2-4 and Figure 2-5 of Chapter 2 because the impact mechanism could not be linked to the AoP natural resources as defined currently.

Crustal scarcity indicator (CSI)

The CSI (Arvidsson et al., 2020) is similar to the ADP ultimate reserve method; however, its characterization factors are calculated without the current production parameter. It strictly represents crustal scarcity rather than a production-to-reserve ratio, which is more consistent according to the authors.

Environmental dissipation potential (EDP) method

The EDP method (van Oers et al., 2020) provides characterization factors for the long-term environmental dissipation potential of resources. The characterization factors are calculated assuming that all of the current primary extraction is equal to long-term dissipation in the environment, with an equation similar to that of ADP. Thus, the resulting characterization factors are the same as those of the ADP ultimate reserve method, the difference being that copper is used as a reference substance

instead of antimony. Moreover, the factors are applied to emission flows in the inventory rather than extraction flows in the life cycle impact assessment step.

Joint Research Centre (JRC)'s suggested approach

The JRC suggested approach allows to quantify dissipative flows of mineral resources at the level of unit processes, in mass units (Beylot et al., 2021, 2020c). It was not yet available for evaluation during the works of the MR taskforce. It is suggested “to take a short-term perspective (25 years), so that any flow of resources to i) environment, ii) final waste disposal facilities and iii) products in use in the technosphere (with low-functional recovery) are reported as dissipative”. Furthermore, it was proposed that dissipative flows could be characterized using the economic value of resources as a proxy to measure the impacts of dissipative flows on the AoP natural resources (Beylot et al., 2020a).

Average dissipation rate (ADR)

The ADR method provides a yearly dissipation rate for metals, providing characterization factors that can be applied to extraction flows in the inventories (Charpentier Poncelet et al., 2021b). All of the flows expected to be emitted to the environment, tailings, landfills or to be non-functionally recycled into other material flows are considered to be dissipative. The dissipation rate is established based on dynamic material flow analysis data covering the global flows for each studied resource. Alike the JRC approach, it focuses on identifying dissipation flows rather than characterizing their impacts; however, the dissipation patterns are representative of the global dissipative flows of resources rather than process-specific as in the case on the JRC suggested approach.

Lost potential service time (LPST)

The LPST method allows to estimate the impacts of dissipative flows, which are the same that are considered in the ADR method (Charpentier Poncelet et al., 2021b). The proposed characterization factors also apply to extraction flows. They allow to estimate the lost potential service that could have been provided by resources in the economy if they had not been dissipated, within time horizons of 25, 100 or 500 years considering the global dissipative flows for each element. It is proposed as a midpoint impact method, which could be complemented with information of the value of the lost service in order to measure endpoint damage.

A.6 Cultural perspectives in the ReCiPe method

To the best of our knowledge, the Eco-indicator 99 method was the first method to integrate cultural perspectives in their impact modelling, based on the works of Hofstetter (Goedkoop and Spriensma, 2001). The ReCiPe method builds on the Eco-indicator 99 method and also integrates cultural

perspectives in the modelling, albeit specifying that they are “*used to group similar types of assumptions and choices*” rather than “*represent archetypes of human behaviour*” (Goedkoop et al., 2013; Huijbregts et al., 2017). In ReCiPe 2016 (Huijbregts et al., 2017), the midpoint impact assessment for mineral resource use is realized using the surplus ore potential (SOP) indicator (Vieira et al., 2017), and the endpoint damage is assessed using the surplus cost potential (SCP) indicator (Vieira et al., 2016). In both methods, (short-term) economic reserves are used to generate characterization factors for the individualist perspective, while (long-term) ultimate recoverable reserves are used to represent the hierarchist and egalitarian perspectives.

As defended in Chapter 2, using single impact pathways is not sufficient to assess the impacts of mineral resource use under given perspectives. Indeed, human values dictates how mineral resources are, or should, be managed. For example, the surplus ore or surplus cost linked to past extraction has not proved to limit the potential to make use of the value of resources, since exploration and technological development so far allowed to produce ever more mineral resources until today. While surplus ore and surplus cost indicators may both be relevant to assess some potential impacts or damage on the AoP natural resources, it is apparent that more discrete links between the cultural perspectives and the impacts mechanisms leading to impacts on the AoP as defined by the Taskforce Mineral Resources (Berger et al., 2020; Sonderegger et al., 2020) are needed. The current assessment with the ReCiPe method may lead to burden shifting to other aspects of resource use that are not accounted for in the method. As a consequence, we estimate that the results of the impact assessment could lead to wrong conclusions from the cultural viewpoint on resource use. Therefore, we propose that additional impact pathways could be adjoined to the ReCiPe method when assessing the impacts of mineral resource use on the AoP natural resources following different cultural perspectives.

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Annex B

This annex presents the supporting information to Chapter 4, submitted as the supplementary information to “Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A, and Sonnemmann, G. Losses and lifetimes of metals in the economy. *Article submitted to Nature Sustainability.*”

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Abbreviations and Acronyms

| | |
|---------------|---|
| BRGM | French geological survey |
| CCA | Chromated copper arsenide |
| DF | Dissipative flows (losses) |
| EMD | Electrolytic manganese dioxide |
| EMM | Electrolytic manganese metal |
| EOL | End-of-life |
| EOL-RR | End-of-life recycling rate |
| EV | Electric vehicles |
| EZC | Enriched zirconium concentrate |
| FCC | Fluid cracking catalysts |
| GSD | Geometric standard deviation |
| HREE | Heavy rare earth elements |
| HSLA | High-strength low-alloy |
| IMoA | International Molybdenum Association |
| ITIA | International Tungsten Industry Association |
| LCD | Liquid crystal display |
| LED | Light-emitting diode |
| LREE | Light rare earth elements |
| MFA | Material flow analysis |
| MRI | Magnetic resonance imaging |
| PCB | Printed circuit boards |
| PET | Polyethylene terephthalate |
| PGM | Platinum group metal |
| REE | Rare earth elements |
| REO | Rare earth oxides |
| UNEP | United Nations Environment Programme |
| US | United States |
| USGS | United States Geological Survey |
| VCM | Vinyl chloride monomers |

B.1 The anthropogenic cycle of metals

The anthropogenic cycle of metals has been extensively described in detail by other authors (Chen and Graedel, 2012; Helbig et al., 2020; Kavlak and Graedel, 2013a; Wang et al., 2007). For easiness, we here reproduced Figure 4-1 (Figure B1). The main processes amongst each life cycle phases are described below.

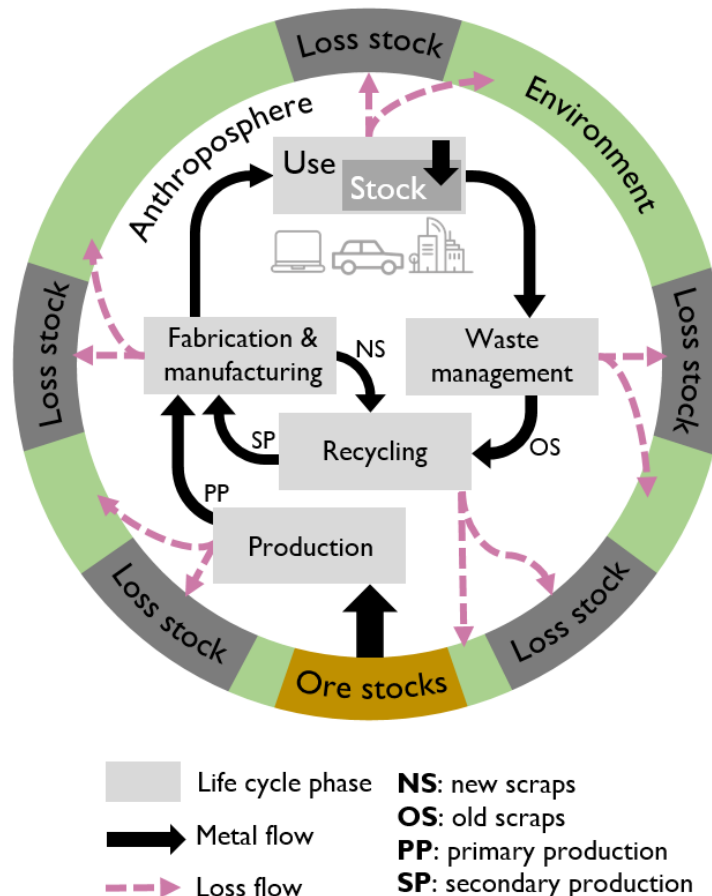


Figure B1. Global cycle of metals (adapted from Chen and Graedel, 2012). Loss flows are either emissions to the environment, non-functionally recycled metals ending up in other material flows, or losses to final waste disposal facilities (landfills, slags and tailings storage facilities).

B.1.1 Production (primary)

Ores are typically extracted from the ground and transformed into refined flows of elements at various degrees of purity (e.g., 3N to 7N) through successive crushing, concentrating, smelting, and refining processes. Metals obtained as by-products may be selectively extracted and refined from different steps of the carrier metal's production. In a few instances, part of the production of elements originates from industrial waste. For example, vanadium may be recovered from spent catalysts used in the petroleum industry in which it tends to accumulate. The production yield is calculated based on

the recovery of elements from ores or other materials in which they are contained and from which they could be recovered, with no regard to the current technical and economic feasibility of production. In the majority of cases, only the ores that are extracted for their content of elements are considered to calculate or estimate the yield of production. However, whenever specific material flows from which elements could be recovered were identified, i.e., because they are knowingly present in such a concentration that it could represent a significant share of the production of that element, and that such material flows were included in a published study as a potential source of that element, these elements were also considered as resources and were accounted for. For example, this was the case for gallium in fly ash (Licht et al., 2015). In a few instances, no production yield could be found for potential by-products. In this case, the production yield is estimated based on the average ore content in comparison to the yearly extraction of such ores and the reported yearly production of the potential by-product (e.g., scandium, Table B16).

B.1.2 Fabrication and manufacturing

Fabrication and manufacturing include every step required to transform refined element flows into final products. Refined elements may be transformed as pure substance flows (e.g., copper) or as more complex materials (e.g., copper alloy). These pure flows or materials are fabricated in semi-products (e.g., sheets, tubes, plates) and further manufactured and assembled into final products.

B.1.3 New scrap recovery

New scraps from the fabrication and manufacturing stage may be collected for recycling. When collected new scraps enter the scrap market, they may be remelted along with virgin raw materials and old scraps. Some collected new scraps may also be recycled internally, as is the case for, e.g., some titanium metal. In such cases, the fabrication and manufacturing yield was estimated to include the potential recovery of new scraps.

B.1.4 Use

The products are readily available to provide their expected functionality to users over their projected lifetimes (i.e., until they become obsolete) or provide their functionality as an expectedly dissipative use (e.g., fireworks, pesticides). Dissipation may occur during the use phase. We distinguish between three types of dissipation during the use phase, referred to as type A, B and C throughout this document.

Type A: This dissipation in use consists of a voluntary dispersion of elements in order to obtain the expected function of the product they are contained in, making it difficult or impossible to recover them. Some may theoretically be re-concentrated through natural cycles in the long-term or

recuperated from the environmental media, such as lead from used ammunitions, or magnesium from ocean water. According to the terminology of Lifset et al. (2012), such dissipation in use corresponds to an intentional release of elements from the intentional use of elements.

Type B: The second type of dissipation in use is a partial dissipation of the metal over its application's lifetime. These dissipative losses are not voluntarily induced to obtain a function but are predicted to occur over the lifetime of applications due to the way metals are used. It is the case of, e.g., steel exposed to the outdoor environment that corrodes over time; of zinc used for galvanization, which is voluntarily sacrificed to improve the longevity of steel applications; of lithium used in lubricating greases that may leak from its application; of platinum group metals (PGM)s used in auto catalytic converters that may be lost due to vibrations; etc. According to the terminology of Lifset et al. (2012), such dissipation in use corresponds to an unintentional release of elements from the intentional use of elements.

Type C: The third type of so-called dissipative uses are expected losses due to the way resources are integrated into a material or product in such a way that their functional recycling is economically or technically unfeasible (e.g., some elements are present in the order of a few parts per million in products reaching EOL, making their separation and recovery inconvenient or impossible even if they are collected as part of the recycling stream). Nonetheless, these elements contribute to the function of the products they are used in over its lifetime, hence not being dissipated (yet). Therefore, it is here considered as dissipated only once the product has become obsolete and entered the waste flow, at which point the resource may be non-functionally recycled or landfilled, becoming inaccessible for future use at least temporarily (cf. discussion in Beylot et al., 2020). These are “lost by design” and correspond to “currently unrecyclable” applications according to the terminology of Ciacchi et al. (2015). In this dataset, such dissipative uses are accounted for as either collection or remelting losses.

We consider dissipation of type A as a punctual dissipative use. Such applications are modeled with a lifetime of one year and a dissipation in use rate of 100%. Hence, they are no longer available for collection and recycling. Dissipation of type B are considered as partial dissipative uses, and a share of elements entering the use phase are reported to be dissipated over the lifetime of products. The remaining share of elements contained in the end-use products, i.e., which have not been dissipated in use, may be collected for recycling. Finally, the elements that are considered to undergo dissipation of type C are assumed to be functionally used throughout the lifetime of the applications. However, they are lost by default (“by design”) to the collection or recycling process since they are considered to be currently unrecyclable, and a collection and sorting yield of 0% is reported for such applications.

B.1.5 Collection and sorting

Obsolete products are collected through waste collection schemes and either landfilled, or dismantled, cleaned, and recycled in new material streams (Chen and Graedel, 2012). Landfilling and non-functional recycling (defined below) are interpreted as dissipation, in line with the rationale of Zimmermann and Gößling-Reisemann (2013) and Helbig et al. (2020).

B.1.6 Recycling (secondary production)

Sorted materials enter the recycling stream and are recycled (generally, remelted) into new materials flows. Elements that enter the recycling streams may either be functionally or non-functionally recycled (Graedel et al., 2011). Non-functional recycling is accounted for as dissipative losses. Functional recycling refers to “that portion of EOL recycling in which the metal [here more generally, the element] in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy” (Graedel et al., 2011). Non-functional recycling refers to “that portion of EOL recycling in which the [element] is collected as old scrap and incorporated in an associated large-magnitude material stream as a 'tramp' or impurity elements” (Graedel et al., 2011). In general, the recycling of elements that can be considered to offset the demand for primary resources can be considered to be functionally recycled. By extension, we consider the recycling of elements present in complex materials into new materials voluntarily making use of primary resources (of that same element) to also consist in functional recycling. For example, this is the case for a fraction of the recycling of magnesia refractories in cement since primary magnesia is also used for cement production (cf. Table B13).

B.2 Methods

B.2.1 Conceptual model

The conceptual model, as presented in the Methods section of Chapter 4, is depicted below.

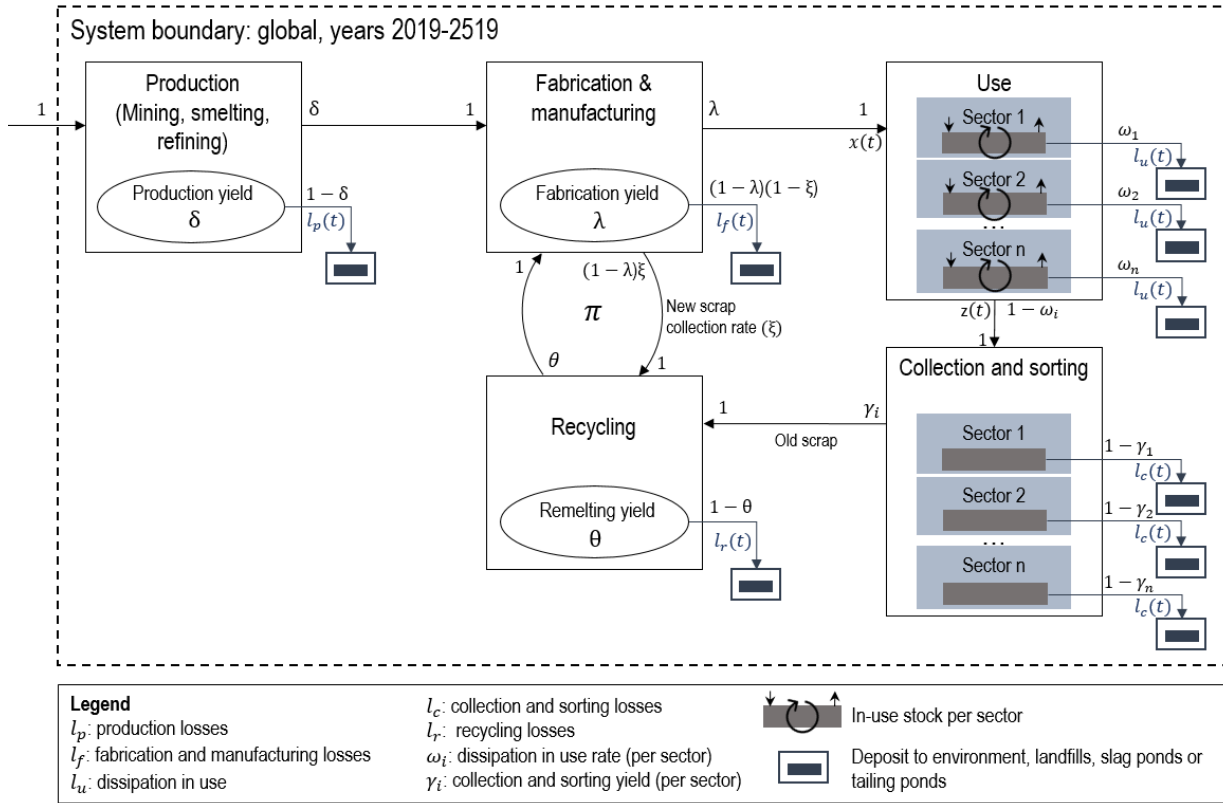


Figure B2. System definition and conceptual model (adapted from Helbig et al., 2020)

B.2.2 Data collection

A wide range of references was consulted to build this dataset. Peer-reviewed literature as well as studies published by governmental institutions, such as the Joint research center (JRC) of the European Commission, the US Geological Survey (USGS), and the French geological survey (BRGM), were preferred. Industrial reports were also often consulted. The most important sources of data to obtain or calculate process yields, end-use distributions, and application lifetimes are presented below.

B.2.2.1 Process yields and dissipation in use

For 18 elements that were already included in a previous study (Helbig et al., 2020), the main process yields were calculated based on global MFA studies from 1997 to 2017. These MFA studies covered the global cycle of aluminium (Bertram et al., 2017), chromium (Johnson et al., 2006), iron (Wang et al., 2007), cobalt (Harper et al., 2012), nickel (Reck and Rotter, 2012), copper (Glöser-Chahoud, 2017),

zinc (Meylan and Reck, 2017), gallium (Licht et al., 2015), germanium (Licht et al., 2015), selenium (Kavlak and Graedel, 2013b), silver (Johnson et al., 2005), indium (Licht et al., 2015), tin (Izard and Müller, 2010), tellurium (Kavlak and Graedel, 2013a), tantalum (Nassar, 2017), tungsten (Meylan et al., 2015), rhenium (Meylan et al., 2015), and lead (Mao et al., 2008a). The process yields calculated by Helbig et al. (2020) based on these MFAs were mostly re-used in the present work. However, some changes were made in order to harmonize the method across all of the studied elements (cf. section B.2.3).

In addition, the Stock and Flows (STAF) and the Criticality of Metals projects of the Center for Industrial Ecology of Yale University provided insights on the life cycle of many other metals. Their criticality studies provided calculated or estimated extraction and refining (production) yields as well as end-of-life recycling rates (EOL-RR) for many elements that they used as inputs for their depletion model (Graedel et al., 2015; Harper et al., 2015; Nassar et al., 2012; Nuss et al., 2014; Panousi et al., 2016). Moreover, Du and Graedel (2011a) provided global MFAs for ten rare earth elements (REE), which allowed calculating process yields for La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Y. However, given the low resolution of the latter MFAs, additional information and data were gathered to complement this study as well as to include the five missing REEs (Er, Ho, Tm, Yb, and Lu) (cf. section B.2.3.3). Moreover, Ciacci et al. (2015) provided valuable insights on the dissipation in use for most of the studied elements, which we largely relied on to establish the rates of dissipation in use across this dataset.

Finally, a short literature survey realized for each element allowed to fill data gaps or make plausible assumptions where necessary. These surveys focused on identifying specific process yields, as well as national statistics or regional MFAs. For example, the USGS released a series of national MFAs for the year 1998, covering 13 elements (USGS, 2004a). Some technical reports or annual reports from mining companies were sometimes also considered as a complementary source of information. Estimations and assumptions are made for processes and elements for which no quantified data is found. The details on the literature underlying each data considered to calculate or report process yields are reported in Table B10-Table B70.

B.2.2.2 End-use distributions

The global distribution of elements into end-use applications was established based on peer-reviewed literature and governmental institutions. The data compiled for Yale University's STAF project, generally representative of the year 2008, was consulted as a starting point to establish end-use distributions for most elements (Ciacci et al., 2015; Graedel et al., 2015, 2013; Harper et al., 2015; Nassar et al., 2012; Nuss et al., 2014; Panousi et al., 2016). A small literature survey was realized for each element in order to update the end-use distributions to a more recent year whenever possible.

For example, the Johnson Matthey's reports were consulted to update the end-use distributions for PGMs for the year 2019 (Johnson Matthey, 2020a, 2020b).

Moreover, the BRGM's criticality sheets (e.g., BRGM, 2018a, 2017a, 2016a) and European Commission's 2020 criticality fact sheets (European Commission, 2020a, 2020b) provided global end-use distributions for several elements, typically for some year between 2010 and 2019. In some cases, market analysis reports or technical reports from industrial sources were available, e.g., for lithium (SQM, 2019) and magnesium (Wietlisbach, 2018).

Furthermore, when additional data was available, end-uses were refined into more precise end-use categories. For example, the USGS reported 65% of lithium uses in batteries for the year 2019 (USGS, 2020). This share was further disaggregated in 44% automotive uses in electric vehicle (EV) batteries and 21% into batteries for consumer electronics based on an industrial report (SQM, 2019). The detailed description of the calculations and references considered to build the end-use distributions for each element are listed in Table B10-Table B70.

B.2.2.3 Managing the diversity of end-use applications

Pragmatic decisions were made in order to keep the number of reported end-use application sectors to a manageable amount. As a rule of thumb, it was attempted not to report a sector including one single element unless it represented an important share of end-uses for that element. In order to cover the wide range of applications reported as "miscellaneous" or "others" across the studied elements, four "other uses" categories were created. They were chosen to reflect the most common applications and the associated lifetimes reported in the literature for such miscellaneous applications. In order to aggregate other uses to one of these categories, we considered the most typical miscellaneous uses reported in the literature for each element. These "other" categories are the following:

- "Other industrial, military & energy applications", including undefined industrial appliances or structural components (e.g., titanium metal used in various industrial applications, aluminum used in petrochemical piping, niobium used in heat-resistant stainless steels in chemical industries or power plants), military and medical appliances, amongst others. Various undefined applications for which relatively long lifetimes were reported in the literature were also aggregated in this category, e.g., for titanium metal (Graedel et al., 2015).
- "Other electrical & metal products" including various electrical components (e.g., switchgear, relays, etc.) and undefined metal components or products (e.g., undefined wrought products and bearings).
- "Other miscellaneous" includes a range of expectedly relatively short-lived applications or components, such as nuclear fuel rods (e.g., zirconium) and spark plugs (e.g., iridium), as well as

undefined other uses for which relatively short lifetimes were suggested in the literature, such as other applications of bismuth, boron, and cobalt (Graedel et al., 2015; Panousi et al., 2016).

- “Other punctual applications” include miscellaneous uses that are inherently dissipative (type A dissipation), such as lead and bismuth used in ammunition, boron used in soaps and detergents, and thulium used as a radiation source for medical imaging. A lifetime of 1 year was reported for these applications, with a dissipation in use rate of 100%.

Moreover, it was observed that the reported end-use distributions of many elements included materials or semi-products (e.g., superalloys, glass, phosphors, rubber, and plastics). When possible, these materials and semi-products were attributed to other end-use sectors based on additional quantitative or qualitative information found in the literature, especially when they covered a significant portion (i.e., >10%) of the end-use distribution for a given element. When it was not possible to do so, they were classified into generic application sectors for materials (i.e., Glass & ceramics, Alloys & solders, and Plastics categories, described below) or into one of the four “other” categories described above.

Multiple elements are used in glass, ceramics, frits, and glazes (e.g., as pigments or to improve their characteristics for certain applications), for which the final end-use sector is seldom reported. Glass products may include, e.g., windows and window doors used in a range of contexts, e.g., construction, refrigerated sections of supermarkets, in specialty laboratory glassware and other glassware, vehicle windshields, etc. Traditional ceramic uses include home applications such as floor and roof tiles, but they can also have a range of technical applications in, e.g., industrial applications and in the aerospace sector. Similarly, the “Alloys and solders” category includes the use of several elements used in, e.g., specialty alloys, superalloys, or as micro-alloying elements, as well as solders that may be used in a variety of contexts and applications (e.g., bismuth and lead solders). Many elements were added to plastic products as fire retardants, stabilizers, and pigments; these were aggregated into one same plastics category.

Moreover, we created an englobing Metallurgy & metalworking (process) category, including multiple process uses. End-uses included in this category consist in dissipative uses of type B. Dissipative uses of type B include metallurgical additives for e.g., deoxidizing and desulfurizing purposes, typically lost to slags (e.g., manganese), and other materials that are expected to be progressively lost to a metal-making process, such as sand casting (e.g., chromite, zircon) or continuous casting (e.g., lithium). Contrastingly, some metallurgical additives are also used to improve the malleability and machinability of metals, which remain in the final product, albeit not contributing to the characteristic of the material or of the product after manufacture. For instance, the addition of tellurium to steel and copper alloys

improves their machinability and remains in the final product (USGS, 2020). While Kavlak and Graedel (2013a) considered such uses to be dissipative, it is possible that elements are actually potentially recoverable during recycling, as in the case of tellurium (Ciacci et al., 2015). In this dataset, the dissipative losses due to such end-uses were considered to be type C dissipation and were reported as either collection or remelting losses.

Finally, it seemed mandatory to distinguish between different end-use sectors for industrial catalysts, batteries, and magnets, because these may have different lifetimes depending on the sector in which they are used and represent important shares of end-uses for many elements. For example, batteries represent major end-uses for e.g., lithium, cobalt, and cadmium, with around 50-70% of their respective consumptions. Different types of catalysts may have different expected lifetimes. For example, Graedel et al. (2015) estimated the use of cobalt catalysts in petroleum refining to have an average lifetime of 2 years, and those for the production of polyester precursors, an average lifetime of 8 years. Therefore, we created two categories for catalysts to reflect such differences: Catalysts (homogenous & aggressive env.) and Catalysts (heterogeneous & stable env.). The former category generally includes catalysts that are in the same phase as reactants for a given process, as well as those used in aggressive environments such as in oxidizing conditions, leading to a need for frequent regeneration or replacement. The latter category generally includes catalysts that are not in the same phase as reactants for a given process and that are not used in particularly aggressive environments.

In the case of batteries, it was often possible to distinguish between those used in consumer electronics, lead-acid batteries, hybrid or electric vehicles, and industrial, utility or energy storage applications. Consequently, three dedicated sectors were created to reflect the variability in lifetimes in between expected lifetimes for batteries, namely batteries (consumer electronics & lead acid), batteries (electric vehicle), and batteries (utility & industrial), with average lifetimes of 4, 9.5 and 13 years, respectively. Similarly, magnet applications were also split into discrete end-use sectors. While they sometimes could be aggregated within the consumer electronics or transport (i.e., electric vehicle engines) sectors based on the available information, some magnets were reportedly used in several other uses such as magnetic resonance imaging (MRI), magnetic cooling, and wind turbines. We classified such expectedly long-lived magnet applications in a generic “Magnets (large)” category for which an average lifetime of 20 years is reported.

B.2.2.4 Application lifetimes and distributions

Elements are distributed into a total of 41 end-use sectors. In order to harmonize the lifetime parameters considered for each end-use sector, elements used in similar applications or in the same end-use sectors are aggregated to the same end-use sector (Helbig et al., 2020). Normal or Weibull

distributions allow taking into account the variability of lifetimes between different potential applications. Both types of distributions are often reported in the literature. Normal distributions are equally distributed around the average lifetime (mean) μ with a standard deviation σ , with all probable values being included in the interval $(-\infty, \infty)$. Weibull distributions sometimes are sometimes a better fit than normal distributions. Moreover, Weibull distributions with a location parameter $y \geq 0$ allow approximating normal distributions, albeit ensuring that all probable lifetimes are greater than zero and are therefore overall well suited for application lifetime distributions. We report normal or Weibull lifetime distributions based on the consulted literature or on estimations. In the dataset, all of the normal distributions are converted into Weibull distributions in order to ensure that all probable lifetime values are non-negative. The method to do so is presented below Table B. When Weibull distributions are reported in the literature with only an average lifetime μ and shape k values, the location (y) value is set to 0, and the scale (λ) value is calculated from the reported μ and k . When average lifetimes are estimated from sources for which no distributions are provided, we report normal distributions with a standard deviation of +/- 10% of the estimated average lifetime, following the method used in Yale's criticality studies, e.g. (Graedel et al., 2015). In some cases, larger standard deviations are estimated to take into account the diversity of potential uses included in a given sector.

Table B1 provides a brief description of each end-use sector and some examples of applications that are included when relevant. For the more generic end-use sectors presented in section B.2.2.3, average lifetimes are estimated based on the most common applications that they include. As an indication, elements for which the application share represents at least 20% of its end-uses are identified. Detailed aggregations into end-use sectors for each element are presented in Table B10-Table B70.

Table B1. End-use sectors, average lifetimes and distributions

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|--|---------------------------|--------------------------|-------------------------------|---|
| Agricultural & environmental applications | | 1 | Fixed | Dissipative uses (e.g., pesticides and fertilizers); cf. section B.2.2.3. |
| Alloys & solders | Bi, Co, Gd, Re, Se, Si, W | 11 | Normal $\sigma = 3.5$ | These values are suggested for nickel- and cobalt-based superalloys used in blades and vanes of aircraft and land-based gas turbines (Nassar, 2017). Shi et al. (2017) report a similar lifetime of 12 years with a standard deviation of 3 years for non-ferrous copper, lead and zinc alloys. It is also estimated to be a reasonable proxy for various solder applications, for which a lifetime of 13.4 years is estimated by other authors |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|---|--------------------|--------------------------|-------------------------------|---|
| | | | | based on the lifetime of electronics (Nassar et al., 2012; Panousi et al., 2016). |
| Aviation | Hf | 40 | Normal $\sigma = 12$ | Average lifetimes of 25 to 40 years are noted as typical (Graedel et al., 2015; Liu et al., 2013). The distribution of Liu and colleagues is reported based on Helbig et al. (2020). |
| Batteries (consumer electronics & lead acid) | Cd, Co, Li, Pb, Sb | 4 | Normal $\sigma = 0.4$ | Estimated lifetimes for batteries used in various consumer electronics or household products varied from about 2.5 to 7 years (Cha et al., 2013; Harper et al., 2012; Sun et al., 2019). A similar average lifetime of 4 years is reported for lead-acid batteries (Harper et al., 2015): both are here aggregated in the same category. A deviation of +/- 10% of the mean value is reported based on Graedel et al. (2015). |
| Batteries (electric vehicle) | As, Li | 9.5 | Normal $\sigma = 0.95$ | Average lifetimes ranging between 8 and 11 years are typical in literature (Bobba et al., 2019; Fu et al., 2020; Richa et al., 2014; Ziemann et al., 2018). |
| Batteries (utility & industrial) | - | 13 | Normal $\sigma = 2.6$ | Lifetimes between 9 and 17 years are typically reported for various utility, industrial, and energy storage batteries (Cha et al., 2013; Harper et al., 2015; Hawkins et al., 2006; Matsuno et al., 2012). Given the diversity of potential applications, we estimate a standard deviation of +/- 20% of the mean value. |
| Biomedical & dental | - | 15 | Normal $\sigma = 1.5$ | Estimated lifetimes vary in function of the applications (e.g., prosthesis, dental implants, and crowns, etc.) and across different references. Given the variety of potential applications and lifetimes, we here assume an average lifetime of 15 years. |
| Catalysts (heterogeneous & stable env.) | Ir, Os, Ru | 12 | Normal $\sigma = 1.2$ | Lifetimes of 8 years up to 15 years are typically reported for several catalyst applications included in this category |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|---|----------------------------------|--------------------------|-------------------------------|--|
| | | | | (e.g., Graedel et al., 2015; Nassar, 2013). This category is used as a proxy for iridium-ruthenium anodes based on their expected lifetime to avoid generating additional sectors for industrial processes. |
| Catalysts (homogenous & aggressive env.) | Hg, Ir | 2 | Normal $\sigma = 0.6$ | Lifetimes ranging between 0.1 and 5 years are typically reported for such catalyst applications (e.g., Graedel et al., 2015; Nassar, 2013; Sun et al., 2019); and an average lifetime of 2 years was considered in this model based on Graedel et al. (2015). This category is used as a proxy for iridium crucibles based on their expected lifetime to avoid generating additional sectors for industrial processes. |
| Chemicals | - | 1 | Normal $\sigma = 0.3$ | Values based on Graedel et al. (2015). This category generally includes chemicals used for undefined processes or applications. |
| Construction | Al, B, Cu, Fe, Mn, Mo, Nb, V, Zn | 50 | Normal $\sigma = 15$ | There is a range of reported lifetimes for construction applications, which may strongly depend on the region in which construction materials are used (e.g., due to earthquakes, etc.). For example, Pauliuk et al. (2013) determine probable average lifetimes for steel used in construction, which could range from 38 to 100 years in their model depending on the world region. Here, an average global lifetime of 50 years with a standard deviation of 15 years is reported based on Helbig et al., (2020), citing Liu et al. (2013). The category also includes fiberglass used for insulation. There may be some degree of overlap between the construction and infrastructure sectors. |
| Cutting tools | W | 1 | Normal $\sigma = 0.3$ | Typical lifetimes reported for carbides and cutting tools included in this category (Graedel et al., 2015; Nassar, 2017). |
| Electronics | Ag, Dy, Er, Ga, Ge, In, Nd, Pr, | 10 | Normal $\sigma = 3$ | This sector includes consumer electronics (e.g., cellphones, televisions, sound systems, and computers) and a range of other electronic appliances or |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|-----------------------------|------------------------|--------------------------|-------------------------------|---|
| | Ru, Sb, Sn, Ta, Te, Tl | | | components that are expected to be used mostly for consumer electronics, such as transistors, capacitors, diodes and hard disk drives, and materials such as semiconductors (e.g., gallium), sputtering targets (e.g., tantalum) and thermal interface materials (indium). Several estimates of lifetimes are available for electronic appliances included in this category, typically ranging between, e.g., 2-4 years for mobile phones, to, e.g., 7-15 years for stereos and televisions (Du and Graedel, 2011b; Graedel et al., 2015; Nassar, 2017). Given the wide range of potential applications that were reported as electronics across the consulted studies, often without further specifications, we report a normal distribution with an average lifetime of 10 years and a standard deviation +/- 30% of the mean value. There may be some degree of overlap between this category and the Other metal products and electronics categories. |
| Glass & ceramics | As, Er, Ho, Se, Y, Zr | 30 | Weibull k = 3.5 | Glass and ceramics were grouped altogether, given the similarities in their wide range of potential applications. This category also includes frits and glazes. Ceramic products include, e.g., homeware, floor and roof tiles, while ceramic components may be used in a range of electronics and automotive applications, amongst many others potential end-use sectors. Glass products or components may be used in a wide variety of applications, such as cooking surfaces, windows, and cookware, lenses and screens used in electronics, amongst many others. Some estimates range between 10 years to 75 years. Given the wide variety of end-uses that are grouped in this sector, we estimate an average lifetime of 30 years, with a Weibull distribution with a shape parameter of 3.5, aligning on the estimate of Graedel |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|--------------------------------------|--------------|--------------------------|-------------------------------|--|
| | | | | et al. (2015) for lithium used in glass and ceramics. |
| Glass manufacturing (process) | - | 2 | Normal $\sigma = 0.2$ | These are average lifetimes reported for platinum-rhodium used in glass manufacturing (Hagelüken, 2003; Nassar, 2013), which is also assumed to represent the lifespan of tin used for the floating glass process (cf. Table B41). The use of cerium and lanthanum as glass polishing powders is classified in other dispersive applications rather than in this category, because the former was estimated to better represent their lifetime for that application. |
| Household appliances | Ni | 14 | Normal $\sigma = 2.8$ | Household appliances include refrigerators, dishwashers, air purification, and air conditioning devices. Typical average lifetimes range between 12 and 15 years (Graedel et al., 2015; Liu et al., 2013). Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. This category may overlap to some extent with the metal goods and the electronics category, for which similar lifetimes are reported. |
| Infrastructure | As, Fe | 40 | Normal $\sigma = 8$ | Includes various applications such as electrical cables, construction materials used for civil engineering, and chromated copper arsenate (CCA) treated wood. There may be some degree of overlap between the construction and infrastructure sectors, and this category may also include industrial infrastructure and pipelines in some cases. The reported values are from Helbig et al. (2020), citing Graedel et al. (2015). |
| Jewelry & investment | Ag, Au, Pt | 30 | Normal $\sigma = 6$ | Average lifetime for jewelry, as reported by Helbig et al. (2020) based on Nassar et al. (2012). Investment products are also included in this category when demand for such products remained positive over a 10-year period (2010-2019), considering that such products may, in theory, |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|-----------------------------|---------------|--------------------------|-------------------------------|--|
| | | | | replace primary production for other applications. A collection yield of 100% was applied to investment products across the dataset; cf. section B.2.3.2 for details. |
| Lighting | Eu, Tb, Y | 2.5 | Normal $\sigma = 0.25$ | The lifetime of lighting applications depends much on consumer's behavior and the specific use and the environment of each lamp (see, e.g. Qu et al., 2017). We estimate an average lifespan of 2.5 years. This value may change between the types of lightbulbs, e.g. for newly commercialized OLEDs; however, the elements reported to be used in lamps in this dataset were mostly used for light-emitting diode (LED) and fluorescent lamps. |
| Magnets (large) | Gd | 20 | Normal $\sigma = 2$ | Includes neodymium permanent magnets used for e.g., wind turbines, gadolinium magnets used for e.g., magnetic cooling, and holmium magnets used for e.g., magnetic flux concentrators. An average lifetime of 20 years is reported based on the lifetime of wind turbines (Du and Graedel, 2011b). Samarium-cobalt magnets are not aggregated in this category as their uses are estimated to be rather well represented by the Other industrial, military & energy applications. |
| Magnets (small) | Sr | 8 | Normal $\sigma = 1.6$ | Includes ferrite magnets and other small or undefined magnets, potentially used in a variety of applications. These are assumed to have an average lifetime of 8 years. Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. |
| Mechanical equipment | Cr, Mo, Ni, V | 35 | Normal $\sigma = 10.5$ | Typical lifetimes of 25-40 years are reported for such applications (Graedel et al., 2015; Liu et al., 2013; Pauliuk et al., 2013). These lifetimes are provided with standard deviations ranging from 2.5 years to 12 years. Given the diversity of potential applications and the diversity of estimated lifetimes and distributions, we estimate an average |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|---|--------------------------------|--------------------------|-------------------------------|---|
| | | | | lifetime of 35 years, with a standard deviation of +/- 30% of the mean value. |
| Metallurgy & metalworking (process) | Mn | 1 | Fixed | Dissipative use of metallurgical additives or other metallurgical processes where elements do not remain in the final product. See section B.2.2.3 for details. |
| Other electrical & metal products | - | 15 | Normal $\sigma = 3$ | Values of 15 years are typically reported for metal products, and 10-20 years for other electrical appliances (Liu et al., 2013; Meylan and Reck, 2017; Pauliuk et al., 2013). An average value of 15 years is reported for this category. Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. There may be some degree of overlap between this category and the electronics and household appliances category. |
| Other industrial, military & energy applications | Be, Ge, Ho, Sm, Ta, Tm, Yb | 20 | Normal $\sigma = 6$ | Lifetime and distribution are based on the values for other titanium uses (Graedel et al., 2015) and other aluminum uses (Liu et al., 2013). See section B.2.2.3 for details. |
| Other miscellaneous | - | 5 | Normal $\sigma = 0.5$ | Lifetime and distribution based on Graedel et al. (2015) and Panousi et al. (2016). See section B.2.2.3 for details. |
| Other punctual applications | Ce, Hg, La, Lu, Os, Sr, Tm, Yb | 1 | Fixed | Dissipative uses; Cf. section B.2.2.3 for details. |
| Packaging | Al | 1 | Normal $\sigma = 0.3$ | Packaging applications included in this category are expected to be mostly single uses. A lifetime of 1 year is reported based on Graedel et al. (2015). |
| Paint | Ti | 20 | Weibull $k = 3.5$ | Values from Graedel et al. (2015) |
| Paper | - | 5 | Weibull $k = 3.5$ | Paper whitening agents and printing inks (titanium) are classified in this category. The lifetime and distribution are from Graedel et al. (2015). |
| Pharmaceutics & cosmetics | - | 1 | Fixed | Dissipative uses; Cf. section B.2.2.3 for details. |
| Photography | - | 30 | Normal $\sigma = 6$ | Silver is used for photography, and a useful lifetime of 30 years is estimated by Nassar et al. (2012). |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|---------------------|--------------|--------------------------|-------------------------------|--|
| Plastics | Ti | 11.5 | Normal $\sigma = 2.3$ | Multiple elements are added to plastic components and products, often PVCs, in the form of, e.g., pigments or chemicals as vulcanizing agents, stabilizers, and flame retardants. These may be used in a variety of applications, and an average lifetime of 11.5 years is estimated based on average lifetimes of 8-15 years reported in the literature for titanium pigments (Graedel et al., 2015) and cadmium stabilizers (Cha et al., 2013). Given the diversity of potential applications, we assume a standard deviation of +/- 20% of the mean value. |
| Protective coatings | - | 9 | Normal $\sigma = 1.8$ | Includes galvanizing, plating and other coatings. In the dataset, the use of protective coatings is often attributed to actual end-use sectors, e.g. for zinc-galvanized steel parts used in the construction and transport sectors. The reported lifetime of 9 years is estimated to be representative of the values for elements included in this end-use sector. These include cadmium, with an estimated lifetime of 7 years (Hawkins et al., 2006), zinc galvanization, with an estimated lifetime of 10 years for its use in industrial and metal working machinery (Meylan and Reck, 2017). In comparison, the estimated average lifetime of 17 years for zinc galvanizing reported by Harper et al. (2015) also includes the use of galvanized steel in the transport and construction sectors, with longer expected lifetimes than those included in this end-use sector. Given the diversity of potential applications, we estimate a standard deviation of +/- 20% of the mean value. |
| Refractories | Mg | 1 | Normal $\sigma = 0.1$ | Horckmans et al. (2019) reported a lifetime of MgO bricks in the order of weeks, while the EC reported a lifetime from weeks to several years for refractory materials based on their quality (European Commission, 2020c). The reported values are from Graedel et al. (2015). |

| End-use sector | ≥20% end-use | Average lifetime (years) | Distribution type & parameter | Description |
|-------------------------------|---|--------------------------|-------------------------------|--|
| Rubber | - | 7 | Normal $\sigma = 1.4$ | Includes vehicle tires, and undefined rubber components (e.g., for vulcanizing agents). An average lifetime of 7 years is reported with a deviation of +/- 20%, considering that average lifetimes range between 4 and 10 years (Ciacci et al., 2015) |
| Solar cells | Te | 30 | Normal $\sigma = 9$ | Helbig et al. (2020), citing Marwede and Reller (2012) |
| Solid oxide fuel cells | Sc | 7 | Normal $\sigma = 0.7$ | Estimate based on Cooper and Brandon (2017) |
| Telecommunication | - | 30 | Normal $\sigma = 6$ | Helbig et al. (2020), citing Glöser et al. (2013) |
| Transport | Be, Bi, Dy, Nb, Pd, Pt, Rh, V, Zn | 20 | Normal $\sigma = 6$ | Transport applications mostly include road vehicles, but may also include boats, trains and railways in some cases. The reported values are the same used by Helbig et al. (2020), based on the value reported for auto and light trucks in Liu et al. (2013), and also considered as the average value for the transport category in the baseline scenario for steel products in the model of Pauliuk et al. (2013). Includes auto catalysts. |
| Well drilling | Ba, Sr | 1 | Fixed | Dissipative use of barium (barytes) and strontium (celestine). |

As noted above, Weibull distributions are automatically derived from normal distributions when these are reported in the dataset. Three variables (location y , scale λ , and shape parameter k) must be defined to obtain a Weibull distribution that matches the mean, the mode, and the variance of the normal distribution. By iteratively updating the estimated shape parameter and recalculating the three parameters λ , k , and y , we approximate the Weibull distribution with the same mean, mode, and variance as the original normal distribution defined by parameters μ and σ . The Weibull distribution strings with defined parameters λ , k , and y are provided in the Supplementary Data.

A system of three equations is resolved by estimating the values of the Gamma function.

- 1) Mean: $\mu = \lambda \Gamma\left(1 + \frac{1}{k}\right) + y$
- 2) Mode: $\mu = \lambda \left(\frac{k-1}{k}\right)^{\frac{1}{k}} + y$
- 3) Variance: $\sigma^2 = \lambda^2 \left(\Gamma\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right) \right)^2 \right)$

As noted above, Weibull distributions reported in the literature did not include location y and scale λ parameters. We assume that, in these cases, location (y) is equal to zero, and the scale is calculated as:

$$4) \lambda = \frac{\mu}{\Gamma(1+1/k)}$$

B.2.3 Additional methods for three groups of elements

Three groups of elements necessitated specific methods to either fill large data gaps or harmonize data. These methods are defined below.

B.2.3.1 Methods for the eighteen elements considered in the “Quantitative assessment of dissipative losses of 18 metals” article of Helbig et al. (2020)

These eighteen elements are aluminum (Table B14), chromium (Table B19), iron (Table B21), cobalt (Table B22), nickel (Table B23), copper (Table B24), zinc (Table B25), gallium (Table B26), germanium (Table B27), selenium (Table B29), silver (Table B38), indium (Table B40), tin (Table B41), tellurium (Table B43), tantalum (Table B60), tungsten (Table B61), rhenium (Table B62), and lead (Table B69).

In order to harmonize the methodologies for all elements in the present study, some changes were made to the parameters used by Helbig et al. (2020). In this dataset, collection rates and dissipation rates are application-specific in addition to being element-specific. Therefore, additional data were collected or calculated to fill these data with updated collection and recycling rates, which are reported for each of the 18 elements in their respective tables included in section B.3 of this Supplementary Information.

Moreover, Helbig et al. (2020) considered inherently dissipative uses (including some dissipation in use of type C) to be dissipated initially during the fabrication and manufacturing step, i.e., before they underwent the use phase. Instead, in the present work, such uses are modeled to be either dissipated over their lifetime (e.g., agricultural products are modeled to be dissipated over one year), either to be dissipated during the collection step for those that are currently unrecyclable as a consequence of the way they are incorporated in products, i.e., “lost by design” (Ciacci et al., 2015). Because of these methodological changes, updated product distribution, and the updated values to sector-specific collection yields, it is possible to observe some variations in the results between both studies.

B.2.3.2 Methods for the Platinum group metals and investment products

Most process yields are calculated based on the works of Nassar (2013). End-use distributions are obtained from Johnson Matthey’s market reports for PGMs covering the past ten years (Johnson

Matthey, 2020a, 2020b, 2015), with the exception of iridium, for which more disaggregated data was available (BRGM, 2020a, based on SFA Oxford, 2020).

For each PGM, the most recent reported distribution is used to calculate the end-use distribution (2019), with the exception of financial (investment) products. The end-use demand for investment products is averaged over ten years in order to smoothen out the effects of the economic cycles on demand for such products. For the years 2010 to 2013, the Johnson Matthey's report from 2015 is considered (Johnson Matthey, 2015), and for the years 2014 to 2019, the reports from 2020 are considered (Johnson Matthey, 2020a, 2020b). The end-use for other sectors is corrected accordingly to still reflect the most recent demand scheme. This is done by estimating the average percentage of demand for investment products over ten years and balancing the remaining uses for the most recent year accordingly. For example, if financial products represent an average of 20% of an element's demand over ten years, the remaining end-uses are determined for a total of 100% (excluding financial uses) and scaled down to 80% of total demand. The same method is applied for other precious metals used in investment products, i.e. silver and gold.

Moreover, in order to harmonize data for high economic value and relatively scarce elements such as PGMs and gold, the production yields were calculated using a similar approach as for gold (cf. Table B66). Nassar (2013) provide generic process yields for concentration, smelting, and refining of PGMs based on a literature review, and the reported values are used for this dataset. The average extraction yield is estimated to be 85% for all PGMs, like gold. Post-mining recovery yields for the other production processes are calculated with the data reported by Nassar (2013) for the different PGMs. While the author applied specific recovery percentages for different mines in some cases, only average values are considered in this dataset. The calculated production yields are generally consistent with values reported in the technical report for the Waterberg Project, which is part of the Bushveld Complex in South Africa (Stantec, 2019). Since the Bushveld Complex holds the largest PGM reserves and produces most of the world's PGMs (Labbé and Dupuy, 2014; USGS, 2020), the reported production yields are estimated to be reasonably accurate.

For other processes, as well as dissipation in use, the yields are also obtained or calculated from the values reported by Nassar (2013) and complemented with additional literature referenced for each PGM, presented in their respective tables: ruthenium, Table B35; rhodium, Table B36; palladium, Table B37; osmium, Table B63; iridium, Table B64; and platinum, Table B65.

B.2.3.3 Methods for the Rare Earth Elements

There are 15 REEs, in addition to which scandium and yttrium are sometimes classified. REEs are often grouped as either light rare earth elements (LREE) or heavy rare earth elements (HREE). We include

yttrium as part of this joint REE methodology, and scandium is considered separately. Promethium is not included in this dataset because it is radioactive and extremely rare. LREEs consist of cerium (Ce), lanthanum (La), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd) and scandium (Sc). HREEs consist of terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), lutetium (Lu), ytterbium (Yb), thulium (Tm), and yttrium (Y).

Du and Graedel (2011a) traced the global anthropogenic cycles for 10 out of 15 REEs in 2007: lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, and yttrium. Based on this work, the yields of production, fabrication and manufacturing, new scrap recovery, collection, and recycling can be calculated. However, the MFAs rely on estimates for the yield of production, and the REE sector has kept developing rapidly in the past decade. Therefore, it is attempted to gather some additional information in order to complement or update the data provided in the study of Du and Graedel (2011a).

Notably, the production yield is recalculated using the methodology of Nassar et al. (2015), considering region- or site-specific compositions of REE ores and estimated processing yields for each of them. This method is detailed in section B.2.3.3.1. Concerning end-use distributions, various studies report disaggregated end-use distributions for each REE separately. These are available for the years 1995-2007 (Du and Graedel, 2013), 2008 (Goonan, 2011a; Nassar et al., 2015), 2010 (Lynas Corporation Ltd., 2010; Peiró et al., 2013) and 2012 (European Commission, 2014). The European Commission (2020a) also reports global aggregated end-use statistics for all REEs for the years 2017 and 2019 and specific end-uses for, e.g., Nd-Fe-B permanent magnets in 2019. The European Commission also describes the different end-uses for all REEs qualitatively and provides quantified end-use applications in Europe in recent years based on European statistics (Eurostat) and Guyonnet et al. (2015). The demand trends for each end-use are also discussed in many of these references.

Finally, Ciacci et al. (2015) provides valuable information on the dissipation in use and the current recyclability of various REE applications. Generally, it is thought that only negligible amounts of REEs are functionally recycled (Graedel et al., 2011; Nassar et al., 2015). However, criticality studies reveal the overall reliance on China for most of the primary production of REEs, which may increasingly drive research for innovative recycling processes to recover secondary REEs. For instance, the BRGM (2016a) suggested that between 10-20% of the supply of dysprosium could result from the recycling of permanent magnets by 2020, based on the projected operation of a pilot plant in 2016. The European criticality study of 2020 also reports significant EoL-Recycling input rates (EOL-RIR) for praseodymium (10%), europium (38%), terbium (6%), and yttrium (31%) (European Commission, 2020a). Therefore,

additional efforts were spent on estimating the current EoL-RRs for REEs in their different application, as presented in section B.2.3.3.5.

B.2.3.3.1 Production yields

Du and Graedel (2011a) proposed global MFAs for 10 REEs in the year 2007, using a top-down approach. The study suggests typical losses of 20% to tailings during concentration and 10% to slag during hydrometallurgy, resulting in a production yield of about 72% for all REEs. A literature survey is undertaken in order to estimate REE-specific production yields.

REEs are mostly produced from bastnaesite, monazite, xenotime, loparite, allanite, and eudialyte ores (Davris et al., 2017). The most important production occurs from bastnaesite in carbonatite-rich deposits of Bayan Obo, China, and Mountain Pass, USA, as well as from the Mount Weld mines in Western Australia (Davris et al., 2017; European Commission, 2020a; USGS, 2020). China produced over 60% of the global REEs in 2019, most of which originated from the Bayan Obo mine (USGS, 2020). The distribution of REEs in the ores differs between deposits, resulting in supply capacity, which may not align with demand. For instance, lanthanum and cerium are currently oversupplied in order to produce enough of the rarer REEs for, e.g., permanent magnets (Alves Dias et al., 2020).

Several estimates of production yields for various deposits are available in the literature. Nassar et al. (2015) mention overall recovery rates (combined yield for extraction, beneficiation, and separation) of 40-60% for bastnaesite deposits in Bayan Obo, 50% for bastnaesite deposits in Sichuan, and 75% for ion-adsorption clay deposits in Southern China, citing (Cheng and Che., 2010). Chen et al. (2017) report recovery efficiencies to concentrates as low as 10% for Bayan Obo in 2011, while recovery rates of rare earth oxides (REO) of 75% and 72.5% are reported for Sichuan and ion-absorbed deposits, respectively. Similarly, Huang et al. (2015) mention potential recovery rates of over 75% for ion-adsorbed using the in-situ leaching method. The Chinese 13th Five-Year Plan established production targets of 75% recovery from the processing of light rare earth ores and ion type rare earth ores, and smelting separation recovery rates of 90% for light rare earth ores and 94% for ion type rare earth ores in 2015 (European Commission, 2020a, table 144). For 2020, the Chinese objectives increased to 80% recovery from the processing of light rare earth ores, 85% for ion type rare earth ores, and aim for smelting recovery rates of 92% and 96% for light rare earth ores and ion type rare earth ores, respectively. These targets and other estimates suggest that the actual recovery of REEs from the Bayan Obo ores should be higher than the 10% reported for lanthanum in 2011 as reported by Chen et al. (2017), and this data was disregarded for this dataset.

In addition to this literature, some technical reports are available. The technical report for preliminary test work realized in the La Paz project in Arizona (World Industrial Minerals, 2020) suggests a

combined recovery of at least 50% REEs for the concentration and hydrometallurgy processes. Roche Engineering (2014) prospected an average recovery yield of 79% for the Bull Hill Mine (Wyoming) over its projected lifetime. The project relies on REE-bearing carbonatite with particularly high REE content (some may undergo hydrometallurgy without prior concentration). SRK Consulting (2010) proposed an Alternative Technical Economic Model for the Mountain Pass Re-Start Project. They estimated an average concentration rate of 65% based on historical production at the Mountain Pass mining site. Moreover, the recovery of 99.8 lb out of 109.9 lb during the extraction/separation processes suggests a projected smelting yield of about 91% (cf. Figure 6.1 of the cited report).

In the Feasibility study for the Nechalacho Rare Earth Elements Project lead by Avalon Rare Metals (Micon International Limited, 2013), it is mentioned that the project relies on similar technologies that are used in China to produce REEs with solvent extraction. The process description for the Nechalacho project is indeed similar to that used to extract REEs from the bastnaesite deposits in the Bayan Obo mine in China (Cf. Davris et al., 2017; Xie et al., 2014). First, a concentrator produces a floatation concentrate from ores through crushing, grinding, flotation and filtration. Then, a hydrometallurgical plant separates the concentrate into a mixed RE precipitate and an enriched zirconium concentrate (EZC). The precipitate is sent to the refinery to produce pure REOs. The EZC may be sold to third parties for further processing. It is said that the client for EZC would likely be located in China. In this feasibility study, the recovery rates for the concentrator pilot plant are estimated to represent recovery yields once operating under optimal conditions (Micon International Limited, 2013). It is noted that the on-site hydrometallurgical recovery of LREEs from LREE-rich ores may be easier than for HREEs, as the latter require the caustic cracking of zircon to improve their leaching to the precipitate. Based on the values provided in table 14.4 of the report (pages 148-149), the calculated on-site production yields ranged between 20% and 47% for HREEs, while that of LREEs ranged between 51% and 70%, suggesting that there may be important differences between the recovery rates for different REEs within the same mining site. When considering the potential further recovery of REEs from the EZC as described above, and assuming that two-thirds of the REE content of EZC will be recovered by the third-party company purchasing the EZC, the following post-mining recovery yields for 15 REEs are calculated: cerium, 75%; lanthanum, 75%; praseodymium, 74%; neodymium, 75%; promethium, 74%; samarium, 73%; europium, 72%; gadolinium, 72%; terbium, 72%; dysprosium, 72%; holmium, 72%; erbium, 71%; lutetium, 68%; ytterbium, 69%; thulium, 70%; and yttrium, 71%.

Moreover, recovery yields for each REE may vary based on the distribution of the different REEs in various deposits as they have different mineralogy settings and different concentrations of various REEs (European Commission, 2020a; Nassar et al., 2015). For instance, Huang et al. (2015) mention that heavier rare earths are more than ten times richer in ion-adsorbed deposits than in ores such as

bastnaesite and monazite. Therefore, more HREEs may originate from ion-adsorbed deposits in comparison to other ores. Nassar et al., (2015) estimate that Southern provinces produced about 29% of the Chinese REE production in 2008 (30 000 tons out of 104 000 tons of REEs), while their production accounted for 91% of the country's total HREE production, with approximately 13 000 tons out of 14 300, and for 19% of the country's total LREE production.

The currently installed production capacity remains mostly in China (Binnemans et al., 2018; Nassar et al., 2015). The Chinese REE industry has been actively aiming to increase its efficiency in the past decade (Shen et al., 2020). Meanwhile, in recent years, an increasing share of REE production has also been occurring outside of China, particularly in Mountain Pass (Molycorp operations in California) and Lynas Corporation in Mount Weld (extraction and concentration in Australia, refining in Malaysia). Important artisanal mining activities also take place in Myanmar, whose concentrates are sent to China for refining (European Commission, 2020a; USGS, 2020).

From this literature survey, it can be expected that the concentration yields are lower, and the smelting yields are similar to the estimated of Du and Graedel (2011a). Because it is not possible to extract single REEs from a mine (Binnemans et al., 2018), the ore composition at different mining sites can provide a reasonable assessment of how many REEs are currently extracted and produced. Element-specific production yields for REEs are thus computed using the methodology of Nassar et al. (2015). It is not possible to improve the method due to the lack of data regarding concentration and smelting yields for specific REEs for the current mining operations. The data required to determine the production yields are the process yields for each main mining site as well the REE-distribution in the REE-ores of each site.

Regarding the composition of REE ores, Nassar et al. (2015) provide the REO distribution for various Chinese mining sites as well as for Mountain Pass (US), India, Perak (Malaysia), Eastern coast (Brazil), and the Lovozero complex (Russia) based on various literature. The composition of Mount Weld ores is estimated based on the composition of the central lanthanide deposit (Jaireth et al., 2014), which is currently exploited by the Lynas Corporation (Lynas Corporation Ltd., 2010). The BRGM provides distributions for similar mining sites or regions as Nassar et al. (2015), based on Roskill Services (cf. table 14 in Bru et al., 2015). Although the values are very similar amongst the provided literature, some minor differences could be found. In the case of conflictual values, the data reported in the BRGM study are considered. Distributions are normalized to 100% when the total REO content is not equal to 100%. Given the dynamics of (often illegal and undocumented) artisanal mining operations in the Jiangxi province, and because of the lack of data on the current production, it is not possible to replicate the distribution of production shares in that province as done by Nassar et al. (2015).

Therefore, the average REO distribution across the Jiangxi province is applied to all of its REO production. Moreover, while Myanmar's artisanal operations provided an important share of the recent years' supply of REEs, no information could be found on their specific REE ores or production. Still, Adamas Intelligence (2019) reported that about 32% of the global dysprosium and terbium production, and that 13% of neodymium and praseodymium global production may have originated from Myanmar in 2018. The USGS also noted that Burma (Myanmar) produced most of the world's yttrium in 2019 along with China, from similar clay deposits as in southern China (USGS, 2020). Without further information, the average distribution of REOs in all of the clay deposits of southern China are applied to the total REO production of Myanmar as a first estimate. The average ore content across the studied deposits are presented in Table B2.

Table B2. Average ore content in REOs in different mining sites or regions (based on Bru et al., 2015 and Nassar et al., 2015). Distributions are normalized to 100% total REO content

| REO | China | | | | | | | | Brazil | India | Russia | United States | Australia | Myanmar |
|----------------------------|-----------|------------------|------------------|-------------------|------------------|---------------------|----------------|---------|---------------|-------------------|------------------|---------------|------------|---------|
| | Bayan Obo | Mianning Sichuan | Weishan Shandong | Jiangxi (average) | Shanghang Fujian | Pingyuan Guang-dong | Jianghua Hunan | Guangxi | Eastern coast | monazite deposits | Lozovero complex | Mountain pass | Mount Weld | N/A* |
| Y_2O_3 | 0.50% | 0.50% | 0.76% | 26.61% | 25.93% | 20.00% | 47.29% | 28.99% | 1.40% | 0.45% | 0.00% | 0.10% | 0.00% | 26.7% |
| La_2O_3 | 22.98% | 29.26% | 35.30% | 21.54% | 27.63% | 30.40% | 15.99% | 24.06% | 23.97% | 22.56% | 27.99% | 33.25% | 25.57% | 22.5% |
| CeO_2 | 49.95% | 50.40% | 47.55% | 11.48% | 2.04% | 1.90% | 0.32% | 0.60% | 46.94% | 48.63% | 57.48% | 49.17% | 46.88% | 9.7% |
| Pr_6O_{11} | 6.19% | 4.61% | 3.93% | 4.74% | 5.85% | 6.60% | 4.39% | 5.56% | 4.49% | 5.61% | 3.80% | 4.31% | 5.34% | 4.9% |
| Nd_2O_3 | 18.48% | 13.03% | 10.85% | 17.12% | 20.04% | 24.40% | 10.33% | 19.80% | 18.48% | 18.55% | 8.80% | 12.02% | 18.55% | 17.7% |
| Sm_2O_3 | 0.80% | 1.50% | 0.79% | 3.44% | 4.24% | 5.20% | 2.42% | 4.38% | 3.00% | 2.71% | 1.00% | 0.80% | 2.28% | 3.6% |
| Eu_2O_3 | 0.20% | 0.20% | 0.13% | 0.44% | 0.88% | 0.70% | 0.10% | 0.72% | 0.10% | 0.02% | 0.13% | 0.10% | 0.44% | 0.5% |
| Gd_2O_3 | 0.70% | 0.50% | 0.53% | 4.20% | 4.28% | 4.80% | 3.95% | 4.35% | 1.00% | 1.20% | 0.20% | 0.20% | 0.75% | 4.2% |
| Tb_4O_7 | 0.10% | 0.00% | 0.14% | 0.80% | 0.75% | 0.60% | 0.97% | 0.62% | 0.10% | 0.06% | 0.07% | 0.02% | 0.07% | 0.8% |
| Dy_2O_3 | 0.10% | 0.00% | 0.00% | 4.20% | 3.81% | 3.60% | 6.23% | 4.06% | 0.40% | 0.18% | 0.09% | 0.03% | 0.12% | 4.2% |
| Ho_2O_3 | 0.00% | 0.00% | 0.00% | 0.91% | 0.42% | 0.00% | 1.20% | 0.77% | 0.00% | 0.02% | 0.03% | 0.00% | 0.00% | 0.8% |
| Er_2O_3 | 0.00% | 0.00% | 0.00% | 2.61% | 2.35% | 1.80% | 3.51% | 2.59% | 0.10% | 0.01% | 0.07% | 0.00% | 0.00% | 2.6% |
| Tm_2O_3 | 0.00% | 0.00% | 0.00% | 0.38% | 0.39% | 0.00% | 0.56% | 0.39% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.4% |
| Yb_2O_3 | 0.00% | 0.00% | 0.03% | 1.32% | 1.01% | 0.00% | 2.37% | 2.66% | 0.02% | 0.00% | 0.30% | 0.00% | 0.00% | 1.3% |
| Lu_2O_3 | 0.00% | 0.00% | 0.00% | 0.20% | 0.37% | 0.00% | 0.38% | 0.45% | 0.00% | 0.00% | 0.05% | 0.00% | 0.00% | 0.2% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

*The distribution of REOs in Myanmar are assumed to be represented by the average composition of clay-deposits in China due to lack of information

The share of production of REEs from the different mines is estimated using USGS statistics for the year 2019 (USGS, 2020) and the share of global production per country or Chinese province in 2019 as reported by Roskill Services statistics, reported in the Figure 337 of the European Commission (2020a). The small share of the production occurring in Vietnam, Thailand, Burundi, and other countries is disregarded from the study. The covered production represents nearly 99% of the total production in 2019 and is assumed to be representative of the global production yield for the year 2019. The estimated production for each region or mine are calculated as shown in Table B3.

Table B3. Estimated REO production per mine or region in 2019 (tons) based on annual production data and region-specific average REO content of the ores reported by the European Commission (2020a)

| Country | China | | | | | | | | Brazil | India | Russia | Unites States | Australia | Myanmar | Other | Total prod. (ton REO) |
|---------------------------------|-----------|------------------|-------------------|---------|-------------------|----------------------|-----------------|---------|----------------|-------------------|------------------|---------------|------------|---------|-------------|-----------------------|
| Mine / region | Bayan Obo | Mianning Sichuan | Weishan Shan-dong | Jiangxi | Shang-hang Fujian | Ping-yuan Guang-dong | Jiang-hua Hunan | Guangxi | East-ern coast | Monazite deposits | Lozovero complex | Mountain pass | Mount Weld | N/A* | Not covered | |
| production of REOs (tons) | 80220 | 9450 | 3990 | 31446 | 2442 | 2772 | 1050 | 630 | 1000 | 3000 | 2700 | 26000 | 21000 | 22000 | 2300 | |
| % of total production | 38% | 5% | 2% | 15% | 1.2% | 1.3% | 0.5% | 0.3% | 0.5% | 1.4% | 1.3% | 12.4% | 10.0% | 10.5% | 1.1% | |
| Y ₂ O ₃ | 401 | 86 | 30 | 8674 | 633 | 302 | 497 | 183 | 14 | 14 | 34 | 0 | 0 | 5904 | N/A | 16770 |
| La ₂ O ₃ | 18432 | 2975 | 1409 | 6610 | 675 | 798 | 168 | 152 | 240 | 674 | 672 | 7703 | 5413 | 4821 | N/A | 50742 |
| CeO ₂ | 40070 | 4506 | 1897 | 3912 | 50 | 144 | 3 | 4 | 469 | 1409 | 1358 | 14197 | 9914 | 2360 | N/A | 80293 |
| Pr ₆ O ₁₁ | 4969 | 388 | 157 | 1393 | 143 | 205 | 46 | 35 | 45 | 168 | 134 | 1019 | 1129 | 1045 | N/A | 10877 |
| Nd ₂ O ₃ | 14826 | 1224 | 433 | 5121 | 489 | 866 | 108 | 125 | 185 | 613 | 403 | 2844 | 3927 | 3850 | N/A | 35015 |
| Sm ₂ O ₃ | 641 | 139 | 31 | 1181 | 103 | 158 | 25 | 28 | 30 | 77 | 17 | 237 | 482 | 858 | N/A | 4008 |
| Eu ₂ O ₃ | 160 | 25 | 5 | 175 | 21 | 17 | 1 | 5 | 1 | 0 | 2 | 0 | 94 | 126 | N/A | 633 |
| Gd ₂ O ₃ | 561 | 62 | 21 | 1436 | 104 | 114 | 41 | 27 | 10 | 37 | 15 | 0 | 0 | 989 | N/A | 3418 |
| Tb ₄ O ₇ | 80 | 8 | 6 | 209 | 18 | 21 | 10 | 4 | 1 | 2 | 0 | 0 | 14 | 150 | N/A | 522 |
| Dy ₂ O ₃ | 80 | 21 | 0 | 1178 | 93 | 76 | 65 | 26 | 4 | 6 | 15 | 0 | 26 | 825 | N/A | 2414 |
| Ho ₂ O ₃ | 0 | 4 | 0 | 235 | 10 | 15 | 13 | 5 | 0 | 1 | 19 | 0 | 0 | 160 | N/A | 461 |
| Er ₂ O ₃ | 0 | 6 | 0 | 682 | 57 | 27 | 37 | 16 | 1 | 0 | 22 | 0 | 0 | 470 | N/A | 1317 |
| Tm ₂ O ₃ | 0 | 2 | 0 | 94 | 10 | 4 | 6 | 2 | 0 | 0 | 3 | 0 | 0 | 66 | N/A | 187 |
| Yb ₂ O ₃ | 0 | 5 | 1 | 476 | 25 | 21 | 25 | 17 | 0 | 0 | 5 | 0 | 0 | 323 | N/A | 898 |
| Lu ₂ O ₃ | 0 | 0 | 0 | 71 | 9 | 4 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 52 | N/A | 143 |

*The distribution of REOs in Myanmar are assumed to be represented by the average composition of clay-deposits in China due to lack of information

The best possible estimates based on the consulted literature are used to establish process yields. We estimate pre-concentration losses of 5% (assuming imperfect in-situ leaching of ion-adsorbed REEs and generic mining losses during open pit mining), and concentration yields of 65% for the Bayan Obo mine, 75% for the Sichuan/Shandong provinces, 80% for all of the ion-adsorbed deposits in southern China, 70% for the Mountain Pass mine and the Mount Weld mines, 75% for the deposits of Myanmar, and 65% for all other mines. A uniform smelting yield of 90% is considered for all REEs, as estimated by Du and Graedel (2011a). Considering these yields and the average share of each REOs in mined ores, it is possible to estimate REO-specific production yields. These are shown in Table B4.

Table B4. Estimated production tonnage, production yield, and total extraction tonnage for 15 REOs in 2019

| REO | Estimated total production in 2019 (excluding Vietnam, Thailand, Burundi & other countries) (tons) | Estimated production yield | Estimated total extraction in 2019 (tons) |
|---------------------------------|--|----------------------------|---|
| Y ₂ O ₃ | 16641 | 66% | 25059 |
| La ₂ O ₃ | 51846 | 60% | 86397 |
| CeO ₂ | 78693 | 58% | 135325 |
| Pr ₆ O ₁₁ | 11103 | 60% | 18646 |
| Nd ₂ O ₃ | 35165 | 60% | 58751 |
| Sm ₂ O ₃ | 3817 | 63% | 6081 |
| Eu ₂ O ₃ | 599 | 62% | 969 |
| Gd ₂ O ₃ | 3452 | 64% | 5395 |
| Tb ₄ O ₇ | 586 | 65% | 906 |
| Dy ₂ O ₃ | 2651 | 66% | 4003 |
| Ho ₂ O ₃ | 496 | 67% | 744 |
| Er ₂ O ₃ | 1545 | 67% | 2315 |
| Tm ₂ O ₃ | 217 | 67% | 325 |
| Yb ₂ O ₃ | 767 | 67% | 1151 |
| Lu ₂ O ₃ | 123 | 67% | 185 |

The average production yield is approximately 60% across the REOs, which is about 12% lower than that calculated with the generic yields utilized in the MFAs of Du and Graedel (2011a). Part of this difference is explicable by the consideration of 5% pre-concentration losses, while the remainder of the difference is due to lower estimated recovery yields from the concentration process of different mining sites in comparison to the estimates of Du and Graedel (2011a). In general, HREEs are observed to have higher production yields than LREEs since they are mostly recovered from the ion adsorbed clay deposits, for which the recovery is estimated to be higher than that from other ores. A notable limitation of the estimated production yields is that average concentration and smelting yields are applied equally to all REEs occurring in a given mining site or region, since no element-specific

concentration yields for different REEs could be determined for current mining and smelting operations. It is likely that these yields do vary to some extent amongst REEs during concentration and separation processes, as previously discussed.

B.2.3.3.2 End-use distribution

Detailed end-use distributions for ten out of fifteen rare earths (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Y) are available in the literature. The most recent available data from various sources are considered to establish end-use distributions (European Commission, 2014; Goonan, 2011a; Peiró et al., 2013). The data from Peiró et al. (2013) are reportedly based on Lynas Corporation Ltd. (2010) and Goonan (2011a). The values reported by Peiró et al. (2013) are more disaggregated than the 2008 distribution of Goonan (2011a). The latter has also been taken up in the Yale studies (Ciacci et al., 2015; Graedel et al., 2013; Nassar et al., 2015). Peiró et al. (2013) disaggregated the use of REEs in phosphors based on the distribution of red, green, and blue phosphors in applications making use of them (liquid crystal displays [LCD]s, plasma panels, and lighting applications). The values in these various references suggest similar distributions of end-uses for REEs between the years 2008 and 2010. The three tables below show the end-use distributions based on Goonan (2011a), Peiró et al. (2013) and European Commission (2014).

Table B5. End-use applications of REOs in 2008 (based on Goonan, 2011a)

| End-use | La ₂ O ₃ | CeO ₂ | Pr ₆ O ₁₁ | Nd ₂ O ₃ | Sm ₂ O ₃ | Eu ₂ O ₃ | Gd ₂ O ₃ | Tb ₄ O ₇ | Dy ₂ O ₃ | Y ₂ O ₃ |
|-----------------------------|--------------------------------|------------------|---------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|-------------------------------|
| Auto-catalytic converters | 1% | 16% | 2% | 1% | 0% | 0% | 0% | 0% | 0% | 0% |
| Ceramics | 3% | 2% | 5% | 4% | 0% | 0% | 0% | 0% | 0% | 32% |
| FCC | 46% | 5% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Glass additives | 7% | 19% | 1% | 2% | 0% | 0% | 0% | 0% | 0% | 2% |
| Metallurgy except batteries | 8% | 14% | 7% | 8% | 0% | 0% | 0% | 0% | 0% | 0% |
| Nd magnets | 0% | 0% | 70% | 76% | 0% | 0% | 69% | 11% | 100% | 0% |
| Battery alloys | 16% | 10% | 5% | 5% | 73% | 100% | 0% | 0% | 0% | 0% |
| Phosphors | 2% | 2% | 0% | 0% | 0% | 0% | 21% | 89% | 0% | 54% |
| Glass polishing | 13% | 25% | 7% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Other | 4% | 7% | 3% | 5% | 27% | 0% | 10% | 0% | 0% | 12% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Table B6. End-use applications of REEs in 2010 (calculated based on Peiró et al., 2013)

| End-use | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Y |
|--------------|----|----|----|----|----|-----|-----|-----|----|-----|
| LCD display | 0% | 0% | 0% | 0% | 0% | 13% | 3% | 17% | 0% | 5% |
| Plasma panel | 0% | 0% | 0% | 0% | 0% | 5% | 1% | 5% | 0% | 2% |
| Lighting | 2% | 2% | 0% | 0% | 0% | 83% | 18% | 67% | 0% | 47% |

| End-use | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Y |
|---|------|------|------|------|------|------|------|------|------|------|
| Internal combustion vehicles | 1% | 17% | 2% | 1% | 0% | 0% | 0% | 0% | 0% | 0% |
| FCC | 44% | 4% | | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Electric vehicle (battery) | 12% | 7% | 5% | 6% | 48% | 0% | 0% | 0% | 0% | 0% |
| Electrical & electronic devices (battery) | 7% | 4% | 0% | 0% | 27% | 0% | 0% | 0% | 0% | 0% |
| Electrical & electronic devices (magnets) | 0% | 0% | 53% | 58% | 0% | 0% | 0% | 0% | 69% | 0% |
| Electric vehicles (magnets / engine) | 0% | 0% | 13% | 13% | 0% | 0% | 0% | 8% | 22% | 0% |
| Wind Turbines | 0% | 0% | 4% | 4% | 0% | 0% | 0% | 2% | 6% | 0% |
| Magnetic resonance imaging (MRI) | 0% | 0% | 2% | 2% | 0% | 0% | 13% | 1% | 3% | 0% |
| Magnetic cooling | 0% | 0% | 0% | 0% | 0% | 0% | 56% | 0% | 0% | 0% |
| Alloys | 6% | 11% | 6% | 6% | 0% | 0% | 0% | 0% | 0% | 0% |
| Glass products | 8% | 20% | 1% | 2% | 0% | 0% | 0% | 0% | 0% | 2% |
| Ceramic industry (additives) | 3% | 2% | 5% | 4% | 0% | 0% | 0% | 0% | 0% | 32% |
| Glass industry (abrasives) | 13% | 24% | 6% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Others | 4% | 7% | 3% | 5% | 25% | 0% | 10% | 0% | 0% | 12% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Table B7. End-use applications of REEs in 2012 (based on European Commission, 2014)

| End-use | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Y | Er | Ho, Tm, Yb, Lu |
|---------------------------|------|------|------|------|------|------|------|------|------|------|------|----------------|
| Magnets | 0% | 0% | 73% | 89% | 97% | 0% | 35% | 24% | 98% | 0% | 0% | 0% |
| Batteries | 26% | 3% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Other metallurgy | 10% | 19% | 4% | 2% | 0% | 0% | 28% | 0% | 0% | 0% | 0% | 0% |
| Fluid cracking catalyst | 44% | 2% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| auto catalyst (transport) | 1% | 13% | 0% | 2% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Other catalyst | 0% | 3% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Polishing | 1% | 36% | 2% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Glass | 5% | 12% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 72% | 0% |
| Phosphors | 1% | 4% | 12% | 1% | 0% | 96% | 23% | 71% | 0% | 79% | 25% | 0% |
| Ceramics | 1% | 1% | 7% | 4% | 0% | 0% | 0% | 0% | 0% | 21% | 0% | 0% |
| Other | 9% | 8% | 2% | 0% | 3% | 4% | 14% | 5% | 2% | 0% | 3% | 100% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Values in Table B6 are based on those of Table B5; yet, they are more disaggregated given the additional data considered by the authors (Peiró et al., 2013). Some variation between end-uses in 2008 (Table B6) and 2012 (Table B7) can be observed. Especially, the end-use sectors reported by the European Commission (2014) diverged from that of Peiró et al. (2013) for praseodymium, neodymium, and samarium. While the European Commission reports that samarium is used mostly in magnets

(cobalt-samarium), the previous studies suggested that the most important uses were in battery alloys. Moreover, the replacement of NiMH batteries with lithium-ion batteries also reduced the demand for mischmetal, typically composed of lanthanum, cerium, praseodymium, and neodymium. However, the distributions for 2012 (Table B7) show that no praseodymium and neodymium is used in NiMH batteries, contradicting the values reported for lanthanum and cerium (as the four elements constitute mischmetal). Therefore, additional steps are undertaken to calculate end-uses for these two REEs.

In order to estimate flows of praseodymium and neodymium used in NiMH batteries, we consider a typical NiMH battery composition. This composition is estimated based on the results of the ProSUM project as published on the Urban Mine Platform's web page (Huisman et al., 2017). It is estimated that mischmetal is composed of approximately 85% lanthanum, 10% cerium, 2% praseodymium, and 3% neodymium. The values suggest a lanthanum-to-cerium ratio of 89:11, slightly different than the 87:13 ratio suggested with the values reported by the European Commission (2014). It is therefore expected to be fairly representative of the generic composition of mischmetal used in batteries. Based on this information, we estimate that a total of 200 tons of praseodymium and 300 tons of neodymium were used as mischmetal in NiMH batteries in 2012. Since these values are significantly higher than those reported as "other" uses for praseodymium and neodymium in the European criticality report (110 and 75 tons, respectively), these values are treated as phantom flows and are added to the reported consumption of praseodymium and neodymium to calculate their end-use distributions in 2012.

In order to establish the final distribution for 2012, the values reported by the European Commission (2014) are disaggregated into more specific sectors when possible, using data of Peiró et al. (2013). The end-use distributions reported in batteries are disaggregated between electric vehicles batteries and electronic devices. Phosphors are disaggregated by color (green, blue, and red) and attributed to LCDs, plasma panels, and lighting applications based on their typical shares between each of these applications. Magnets are split between MRI, magnetic cooling, electrical & electronic devices, and electric vehicles (engine). Since Peiró et al. (2013) did not report the use of praseodymium and neodymium in NiMH batteries used in electronic devices, their shares are disaggregated between end-use sectors using the same ratio observed for cerium and lanthanum: 64% of batteries used in vehicles, and 36% used in electronic devices. Finally, the various end-use applications are re-aggregated into final end-use categories in order to match our end-use sectors presented in section B.2.2.4.

Moreover, since end-uses for erbium, holmium, thulium, ytterbium, and lutetium were not precisely reported in any of these references, their end-use distributions were estimated based on various

literature sources. The share of end-uses and references utilized to determine end-use sectors for each REE are specified individually in their respective tables presented in section B.3.

B.2.3.3.3 Fabrication & manufacturing and new scrap recovery yields

Given the diversity of applications and the overall paucity of data on specific REEs processes, the fabrication and manufacturing as well as new scrap recovery yields are calculated for 10 REEs based on the MFA data of Du and Graedel (2011a). Fabrication and manufacturing yields are estimated for the five other REEs based on these MFAs. It is assumed that the fabrication and manufacturing yields remain constant, although the share of various end-uses may have evolved over time. Moreover, the recovery and recycling of new and old scrap are not expected to occur for holmium, thulium, ytterbium, and lutetium (European Commission, 2020a).

B.2.3.3.4 Dissipation in use

Dissipation in use is reported based on the works of Ciacci et al. (2015). Notably, the authors report 3% losses of lanthanum and cerium used in polishing powders for the glass industry due to volatilization, as well as 2% losses from the use of REEs in auto catalysts like PGMs used in that same application.

B.2.3.3.5 Recycling

It is challenging to recycle rare earths economically (Bru et al., 2015; Reimer et al., 2018). It is also difficult to assess the current recycling rates of REEs, as many relatively new applications such as wind turbines have not yet reached their end-of-life and as recycling projects aiming to recover REE from spent applications are still mostly in early-stage developments (Bru et al., 2015; Ciacci et al., 2019). All REEs were reported to have recycling rates below 1% around 2010 (Graedel et al., 2011). However, some recovery may occur for a few REEs currently. Notably, Binnemans et al. (2013) mention that magnets, batteries, and lamp phosphors are key applications in terms of recycling potentials. Similarly, the European Commission (2020a) notes that some technologies exist to recycle new or old scraps of magnets, batteries, and phosphors, while they may not always be economically competitive against the cost of primary production. The European Commission also notes that polishing powders may be re-used in the form of mischmetal in Japan and that ongoing research may enable to recover REOs from fluid cracking catalysts (FCC), although it remains unlikely to be economically feasible for lanthanum and cerium. The USGS reports that limited quantities of REEs are currently recovered from batteries, permanent magnets, and fluorescent lamps (USGS, 2020). REEs are seemingly not readily recyclable from other applications currently (Ciacci et al., 2015).

Binnemans et al. (2013) predicted pessimistic versus optimistic global EoL-RR for REEs used in magnets, NiMH batteries, and lamp phosphors by 2020. They anticipated EOL-RRs of 16.5%-33% for REES in

magnets, 20%-35% from batteries, and 32-56% for REEs in lamp phosphors. Out of phosphors used in lighting applications, the yttrium-europium green phosphors are thought to be most readily recyclable due to the ease of the recycling process and the higher economic value of these elements (Binnemans and Jones, 2014). On the other hand, green phosphors containing lanthanum, cerium, gadolinium, terbium, and especially the blue phosphors also containing europium, are much more difficult to recycle (Binnemans and Jones, 2014). For this reason, the authors mention that some recycling processes may only target the recovery of yttrium and europium from green phosphors. Moreover, while NiMH batteries were reportedly using mischmetal in 2008, these were expected to be mostly replaced by REE-free lithium-ion batteries in the future (Goonan, 2011a; Guyonnet et al., 2015). In the end-use distribution of REEs in 2012 considered in this dataset, only lanthanum and cerium were still reportedly used in batteries, suggesting that a small share of praseodymium and neodymium was still used in mischmetal for that application. Nonetheless, we estimated shares of praseodymium and neodymium used in this application in 2012 (section B.2.3.3.2), which could also be functionally recyclable.

In Europe, the most targeted REEs for recovery are praseodymium, europium, yttrium, and terbium, for which EoL-RIR of 10%, 38%, 31%, and 6% are reported, respectively (European Commission, 2020a). However, Europe processes only a small fraction of REEs in comparison to its imports of REEs in final products, partly explaining these relatively high EoL-RIRs. Moreover, the data underlying the European criticality studies suggest a global EoL-RIR of 1% for cerium, lanthanum, samarium, and gadolinium, and of 10% for praseodymium (Deloitte Sustainability et al., 2017; European Commission, 2020a). Given the paucity of data on single EOL-RRs per application and per REE, we estimated EOL-RR for different REEs and different applications based on the quantitative and qualitative information available, as detailed below. In general, it is estimated that the current EoL-RR is much below those suggested in the pessimist scenario for the year 2020, as anticipated by (Binnemans et al., 2013).

B.2.3.3.6 EoL Recycling of cerium and lanthanum from spent polishing powders and FCCs

Although both cerium and lanthanum could be regenerated in spent FCC and polishing powders in some cases (Goonan, 2011a; Vogt and Weckhuysen, 2015), such recovery is assumed to be accounted for in the lifetime distribution and dissipation in use modeling for these applications. Therefore, no collection and recycling is reported to occur for these applications in this dataset.

B.2.3.3.7 EoL Recycling of REE from mischmetal used in NiMH batteries

It is estimated that few efforts would be put to separate and recycle cerium and lanthanum since they are currently in oversupply due to the production of rarer REEs. An assumption of 5% EoL-RR from

mischmetal used for NiMH batteries was considered for cerium, lanthanum, neodymium, and praseodymium.

B.2.3.3.8 EoL Recycling of REE from phosphors in lighting applications

There seems to be a small amount of REEs recovered from lighting applications. To the best of our knowledge, there the amounts of recycling of phosphors outside of Europe are also small, and we use values for Europe as a proxy for global EoL-RRs. The reported recycled quantities from European MSA studies (BIO by Deloitte, 2015) were used to estimate a global EoL-RR for europium, yttrium, and terbium used in lighting applications. In 2013, 33.5 tons of europium, 362 tons of yttrium, and 21.7 tons of terbium were functionally recycled in Europe (BIO by Deloitte, 2015). Comparing these values with the consumption of the same REEs for lighting applications between 2012-2016 as reported by the European Commission (2020a) and the relative share of REEs in lighting applications in 2012, we estimated EoL-RRs of 10% for yttrium and europium, and 20% for terbium. Given the discrepancy between these values and the qualitative information found in literature, as well as the high uncertainty reported for recycling in these MSA studies, an EoL-RR of 10% is reported for these 3 REEs. Finally, Ciacci et al. (2015) mention that cerium is almost exclusively recycled from phosphors, and we assume EoL-RRs of 5% for the less valuable cerium and lanthanum. It is further assumed to be representative of the EoL-RR of gadolinium. An EoL-RR of 0% is estimated for other REEs contained in lighting applications.

B.2.3.3.9 EoL Recycling of REE from permanent magnets

While it has been estimated that the recovery of dysprosium from spent magnets could reach 10 to 20% of supply by 2020 (BRGM, 2016a) and that 170 to 230 tons of neodymium could be recovered per annum in Europe by 2020 (Guyonnet et al., 2015), no approach has been developed beyond pilot plants and the recycling of EoL magnets remains at a standstill in Europe (European Commission, 2020a; Reimer et al., 2018). Similarly, no evidence of an installed industrial recycling capacity in the US for either new or old magnet scraps could be found.

Moreover, it was investigated whether some EoL recycling of REEs could occur in other countries processing most of the REEs, i.e., Japan and China (Du and Graedel, 2011a; Reimer et al., 2018), as they are more likely to be the ones able to recycle REEs (Ciacci et al., 2019). According to the SFA of dysprosium in Japan in 2008 (Shi et al., 2010), about 30% of dysprosium of the EOL dysprosium was recycled in other material cycles. However, in the subsequent dynamic SFA of neodymium and dysprosium in Japan, including one of the authors of the previous study, Sekine et al. (2017) report that these REEs in motors are seldom domestically recovered, as most scrap is either exported, either non-functionally recycled as steel scrap. Thus, we assumed that recovery reported by Shi et al. (2010)

referred to non-functional recycling. Similarly, no recycling of neodymium seemed to have occurred from magnets in China between 2002 and 2011, according to an SFA of Chen et al. (2018). In an SFA of neodymium in China in 2016, Geng et al. (2020) mention that a small part of neodymium inputs originate from the recycling of EoL neodymium products; however, the value is aggregated with the inputs from stockpile materials. Without further information, we assumed that the recycling of magnets was still globally negligible today, and an EoL-RR of 0% was considered for each end-use sector making use of magnets.

B.2.3.3.10 Recycling of other REEs and other applications

EoL-RRs of 0% are reported for other applications (e.g., ceramics, alloys), as well as for all end-uses of erbium, holmium, lutetium, ytterbium, and thulium. This is justified by the small amounts of highly dispersed REEs and the end-use applications in which they are found, as well as the current unfeasibility of their recycling (Ciacci et al., 2015). The table below presents the estimated global EoL-RR for various REEs based on their end-use application.

Table B8. Overview of estimated EoL-RR for REEs in potentially recyclable applications. N/A = not applicable (no share of end-uses attributed to that end-use sector)

| End-use sector | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Y | Other REEs |
|----------------------------------|----|----|----|----|-----|-----|-----|-----|-----|-----|------------|
| Magnets | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Phosphors (lighting application) | 5% | 5% | 0% | 0% | N/A | 10% | 5% | 10% | N/A | 10% | 0% |
| Batteries (NiMH) | 5% | 5% | 5% | 5% | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Other applications | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

B.2.4 Uncertainty evaluation

Uncertainty is inherent to any statistic or data point, and this dataset does not go without its share of uncertainties. We use a Monte Carlo simulation of 1000 iterations to obtain a 95% interval on the key results of the model. The uncertainty is approximated for each data point using a Pedigree-like matrix originally proposed by Weidema and Wesnæs (1996). The matrix is modified to reflect uncertainty on the end-use distributions and process yields reported in this dataset and allow to estimate variance for each data point. Five parameters are included in the rubric, as presented in Table B9.

Table B9. Data uncertainty rubric for the end-use distributions and process yields, and their associated GSD² (adapted from Ciroth et al., 2016 and Graedel et al., 2012)

| Uncertainty level | 1 | 2 | 3 | 4 |
|--|--|---|---|--|
| Reliability (U1) | Verified data published in peer-reviewed manuscript or equivalent | Non-verified data reported by governmental, non-governmental agencies, scientific working groups, commercial entities, or equivalent | Non-verified and/or unpublished results, including personal communications, expert estimates, and interpolations OR calculated based on low-resolution data (one significant digit) | Rough estimate with expectedly large uncertainty |
| | 1.00 | 1.10 | 1.20 | 1.40 |
| Temporal correlation (U2) | Representative for a year between 2017 and 2019, or covering a range of years between 2014 and 2019. | Representative of a year between 2012 and 2016, or covering a range of years between 2010 and 2016. | Representative of a year between 2007 and 2011, or covering a range of years between 2006 and 2013. | Representative of a year prior to 2007, or covering a range of years before 2008. |
| | 1.00 | 1.03 | 1.06 | 1.10 |
| Geographical & technological correlation (U3) | Representative of the global scope at the time of the reported data | Extrapolated from regional data estimated to represent >75% of the global end-use or global processing technology, at the time of the reported data | Extrapolated from regional data estimated to represent 50-75% of the global end-use or global processing technology, at the time of the reported data | Extrapolated from regional data estimated to represent <50% of the global end-use or global processing technology at the time of the reported data |
| | 1.00 | 1.03 | 1.08 | 1.15 |
| Corroboration (U4) | Multiple independent sources indicating data are in strong agreement | At least two independent sources indicating data are in moderately strong agreement | Single source or independent sources indicating results are only in fair agreement | <i>not applicable</i> |
| | 1.00 | 1.10 | 1.20 | |
| Base & exogenous uncertainty (U5) | Stable supply chains (e.g. large magnitude flows and long-lived processes) | Moderately stable supply chains | Dynamic or unstable supply chains & rapid technological and process development | <i>not applicable</i> |
| | 1.05 | 1.10 | 1.20 | |

The reliability of the background data sources (U1) is evaluated, as well as its temporal correlation (U2). Since the model and data are meant to be as representative as possible of the contemporary state of the global anthropogenic cycles of elements, U2 is evaluated using the year 2019 as a reference year. The geographical and/or technological representativeness of the data is evaluated (U3) since it is attempted to provide end-use distributions and process yields representative of the global average. The corroboration of the reported data (U4) is evaluated in line with Graedel et al. (2012). Finally, an exogenous uncertainty parameter (U5) is included in the uncertainty assessment in order to take into account the uncertainty linked to the background data (e.g., potential human errors in calculations), as well as the exogenous uncertainty linked to the apparent stability or dynamics of the studied end-

use distributions (i.e., market for a resource) or that of supply chains and processing technologies used over time. In the most optimal case, $U_5 = 1$ is attributed a base GSD^2 of 1.05, which increases based on the apparent stability of processes, supply chains, and markets for each element, allowing to further consider the likeliness of the reported data with regards to the temporal (U_2) and geographical/technological (U_3) representativeness. U_5 may be evaluated differently between the end-use distributions and processes for one same element.

The basic idea of estimating GSD^2 with the Pedigree matrix calculations is to get to a 95% confidence interval $[\frac{\mu_g}{GSD^2}; GSD^2 \cdot \mu_g]$ (Muller et al. 2012). Graedel et al. (2012) does it similarly with the following calculation:

$$GSD^2 = e^{\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2}}$$

This way, two standard deviations, or 95% of all randomly drawn samples, are within this 95% confidence interval, assuming a log-normal distribution.

B.2.4.1 Uncertainty evaluation - data

The evaluation of uncertainty for process yields is meant to represent as accurately as possible the uncertainty of the actual root source of information that was utilized to calculate a yield or that was reported as such in the dataset. For example, the production yield of 76% reported for strontium is reportedly based on an informed estimate (Panousi et al., 2016), and U_1 for this data is evaluated to be 3 ($GSD^2 = 1.20$).

For the 18 elements for which global material flow analysis underlying the study of Helbig et al. (2020), uncertainty is assessed based on the background MFA studies. As only a few of these studies reported uncertainties, we estimate that each of these background documents relied on reasonably solid mass balanced models at the global scale, assuming a corroboration corresponding to a moderately strong agreement ($U_4 = 2$). For these statistics, uncertainty may have been reported differently whenever other or more recent data was taken into account.

The evaluation of the uncertainty for the dissipation in use parameter is based on a simplified approach in comparison to that of process yields. Since dissipation in use for specific applications is not expected to evolve over time, and as the reported values are estimated to represent an average global dissipation rate, no uncertainty is reported for U_2 , U_3 , and U_5 across all elements and applications. Moreover, since most values are based on the works of Ciacci et al. (2015), itself relying on other sources or informed estimates, we estimate the U_1 and U_4 values for each of these data based on the nature of the background information reported by the authors. The same procedure is used to

estimate uncertainty when other references are considered. Moreover, the values for applications for which no dissipation in use is expected to occur due to the nature of the applications are considered reliable ($U1 = 1$). Finally, no uncertainty is reported for specific sectors that are inherently dissipative uses of type A or B, i.e., the agricultural & environmental applications (type A), metallurgy & metal-making (process) (type B), other punctual applications (type A or B), pharmaceutical & cosmetics (type A), and well-drilling sectors (type A).

As an example, we here briefly exemplify the evaluation of uncertainty of the end-use distribution of lithium. Lithium's end-use distribution is based on industry reports and governmental data, hence $U1 = 2$ ($GSD^2 = 1.10$). The distribution is representative of the global distribution for the year 2019 ($U2 = 1$; $GSD^2 = 1.00$ and $U3 = 1$; $GSD^2 = 1.00$), and it is based on multiple sources that are in strong agreement ($U4 = 1$; $GSD^2 = 1.00$). Since lithium supply for lithium-ion batteries increased rapidly in the past decade and is an important end-use, its $U5$ parameter is evaluated as 3 ($GSD^2 = 1.20$). Based on this evaluation, the resulting standard deviation remains relatively low ($GSD = 1.11$).

B.2.4.2 Uncertainty calculation - standard deviation and the beta distribution

Since process yields are inherently comprised between 0 and 100%, beta distributions are computed using the average value and estimated variance of the data point. Similarly, since the share for each end-use sector must also be included between 0 and 100%, while the sum of the distribution must be equal to 100%, multivariate beta distributions were applied for each end-use distribution depending on the estimated uncertainty for the end-use distribution for each element (Dirichlet distribution).

B.2.4.3 Uncorrelated parameters with a lower and upper bound

Uncertainty of parameters with a lower bound of 0 and upper bound of 1 (e.g., fabrication yield) is considered with the beta distribution, which has two degrees of freedom: parameters α, β .

$$f(x; \alpha, \beta) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1-x)^{\beta-1}$$

where $B(\alpha, \beta)$ is the beta function with $\alpha, \beta > 0$:

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha + \beta)}$$

Mean and variance can be calculated from α and β :

$$\mu = E[X] = \frac{\alpha}{\alpha + \beta}$$

$$\sigma^2 = \text{Var}[X] = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}$$

Likewise, α and β can be calculated easily with the method of moments from a known expectation value and its variance if $\sigma^2 < \mu(1 - \mu)$:

$$\alpha = \left(\frac{\mu(1 - \mu)}{\sigma^2} - 1 \right) \mu$$

$$\beta = \left(\frac{\mu(1 - \mu)}{\sigma^2} - 1 \right) (1 - \mu)$$

B.2.4.4 Using the pedigree matrix with beta distributions

In order to generate α and β , we need to estimate the mean and the variance, or any other set of two equivalent statistical parameters. The cumulative distribution function of the beta distribution is the regularized incomplete beta function $I_x(\alpha, \beta)$.

Beta distributions following the two following properties can be defined, considering that the variance is defined by the square of the standard deviation σ , which can be approximated with the upper half of the 68% confidence interval of the log-normal distribution characterized by a mean of 0.5 and a given geometric standard deviation GSD :

$$1) \quad \mu = E[X] = \frac{\alpha}{\alpha + \beta}$$

$$2) \quad ((GSD - 1) \cdot 0.5)^2 \approx \text{Var}[X] = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}$$

The method of moments described above allows generating the values for α and β of beta distributions for each datapoint, with the condition $(GSD - 1)^2 < 4\mu(1 - \mu)$:

$$\alpha = \left(\frac{4\mu(1 - \mu)}{(GSD - 1)^2} - 1 \right) \mu$$

$$\beta = \left(\frac{4\mu(1 - \mu)}{(GSD - 1)^2} - 1 \right) (1 - \mu)$$

For computational reasons, alpha or beta values were required to be greater than 1 to ensure that all random variables are within the interval $(0, 1)$, but neither 0 nor 1. Whenever the resulting alpha or beta values were lower than one for a given data point, both values were normalized so that the lowest value equaled 1. The other value was augmented proportionally so that the mean value remained the same.

B.3 Data, references and result graphs per metal

B.3.1 MaTrace dataset to be used with the ODYM framework

ODYM is an open software framework for studying dynamic material systems (Pauliuk and Heeren, 2019). Online documentation is available at: <https://github.com/IndEcol/ODYM>.

The dataset and code underlying our work are provided in an ODYM-ready format, and are available on the OSF platform using links provided in Chapter 4.

B.3.2 Tables and result figures per metal

The tables included in this subsection present the values reported or used to calculate each data point included in the dataset and their references, and provide complementary descriptions or explanations. Result graphs from the MaTrace model for all metals are depicted under their corresponding tables (Figure B3 to Figure B63). Numerical values underlying these figures are provided in the Supplementary Data.

B.3.2.1 Lithium**Table B10. Lithium.**

| Lithium | Li, element number 3 | Uncertainty | | | | | | | | | | | | | | | | |
|--|---|--|-----|------------------------------|-----|--|----|------------------|-----|----------------------|----|-------------------------------------|----|-----------------------------------|----|---------------------|----|---|
| End-uses | <p>Recent end-use distributions for lithium are available for 2015 (BRGM, 2017b), and 2019 (SQM, 2019; USGS, 2020). The demand of lithium for batteries has followed a strong trend over the studied years, increasing from 37% to over 60% of the global demand between 2015 and 2019.</p> <p>For this dataset, the distribution of end-use lithium ion batteries from the USGS (2020) is disaggregated into electric vehicle (about 67% of lithium use for batteries) and other batteries (about 33% of lithium use for batteries) based on SQM (2019). Air conditioning was reported as a household appliance. Lubricating greases were reported to have an average lifetime of 10 years and are used in a range of applications such as induced draught fans and lubricated-for-life bearings (Graedel et al., 2015). These were here classified in the Other electrical & metal products. The following estimates for end-use are thought to be representative global yearly averages for the year 2019:</p> <table><tr><td>Batteries (consumer electronics & lead acid)</td><td>21%</td></tr><tr><td>Batteries (electric vehicle)</td><td>44%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>3%</td></tr><tr><td>Glass & ceramics</td><td>18%</td></tr><tr><td>Household appliances</td><td>3%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>3%</td></tr><tr><td>Other electrical & metal products</td><td>5%</td></tr><tr><td>Other miscellaneous</td><td>5%</td></tr></table> | Batteries (consumer electronics & lead acid) | 21% | Batteries (electric vehicle) | 44% | Catalysts (homogenous & aggressive env.) | 3% | Glass & ceramics | 18% | Household appliances | 3% | Metallurgy & metalworking (process) | 3% | Other electrical & metal products | 5% | Other miscellaneous | 5% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 3 |
| Batteries (consumer electronics & lead acid) | 21% | | | | | | | | | | | | | | | | | |
| Batteries (electric vehicle) | 44% | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 3% | | | | | | | | | | | | | | | | | |
| Glass & ceramics | 18% | | | | | | | | | | | | | | | | | |
| Household appliances | 3% | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 3% | | | | | | | | | | | | | | | | | |
| Other electrical & metal products | 5% | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 5% | | | | | | | | | | | | | | | | | |
| Production yield | <p>The production of lithium occurs from both brines and ores. The production loss from brine is estimated at 33% based on Evans (2014), Foss et al. (2016), and Houston and Gunn (2011). The production losses from ores (e.g., spodumene) are estimated to be of 30% for extraction (proxy for spodumene ores), with an additional 15% refining loss (Graedel et al., 2015).</p> <p>The share of lithium production from ores and brines is calculated based on each country’s share of total production for 2019 (USGS, 2020) and on their respective production method (brine or ores) as reported by Goonan (2012). Based on Chinese production in 2008, it is estimated that China produces 880t/(880t+2410t) = 78.5% lithium from brines (Goonan, 2012).</p> <p>The US production is undisclosed in the USGS statistics. Although US production was historically important, it seems to have remained marginal in the recent years, since the only active mine was the Silver Peak brine mine. For instance, the BRGM estimated that lithium production at the Silver Peak site was around 2 000 tons in 2018 (BRGM, 2020b), which represented around 2% of the total production during that year. Therefore, it was considered to be negligible and not considered for</p> | U1: 3 U2: 4 U3: 1 U4: 3 U5: 2 | | | | | | | | | | | | | | | | |

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| | the calculation of the production yield. Based on this information, we calculated a production yield of 70%. | |
| Fabrication and manufacturing | While some MFAs of lithium and lithium-ion batteries have been published (Calisaya-Azpilcueta et al., 2020; Hao et al., 2017; Liu et al., 2021), none provide specific information on fabrication and manufacturing yields. The Clean Energy Manufacturing Analysis Center (CEMAC) estimated that yields for lithium-ion cell manufacturers range between 70-90% depending e.g. on the maturity of the processing firms (Chung et al., 2016). The relatively low yield is reportedly due to difficulties with precisely and consistently controlling the electrochemical reactions utilized in the battery manufacturing process (Chung et al., 2016). Based on the latter reference, we estimate the average fabrication and manufacturing yield for batteries to be of 80% globally, while the manufacturing of other lithium applications is assumed to be of 90%. Taking into account the respective share of lithium in battery and other applications, the resulting overall yield is calculated to be of 84%. | U1: 2 U2: 2 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | The studied MFAs of lithium suggest that there is no recycling of lithium new scraps. The recycling of new scraps, if any, is considered to be done on-site and to be included in the yield of fabrication and manufacturing. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | 85% (assumption) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Dissipation in use | Pharmaceuticals and lubricants may be assumed to be lost during use (Ziemann et al., dissipated 2012). While pharmaceutical products can be expected to be consistently dissipated during use, Graedel et al. (2015) noted that lubricants are rather long-lived and that in some cases may even remain in the product for its entire lifetime, such as in lubricated-for-life bearings. We assume a dissipation in use of 80% of lithium lubricants (aggregated in the Other electrical & metal products). Moreover, a dissipation in use of 100% is reported for lithium used in continuous casting and catalysts. Furthermore, we estimated that no dissipation in use occurs from other applications of lithium. | Per sector; please refer to Supplementary Data |
| Collection and sorting | The European Commission (2020a) reported that lithium may only be recovered from batteries. Graedel et al. (2015) estimated a 10% EoL-RR for lithium in battery applications based on an MFA for cobalt (Harper et al., 2012), and 0% for other applications. Europe now has an installed recycling capacity of over 40,000 tons of LIBs per year (European Commission, 2020a); however, the recycling of lithium remains challenging. There is some evidence suggests that the global EoL-RR of lithium batteries remains lower than 10%, as the global EoL-RR of lithium is estimated remain around 1% since 2010 (BRGM, 2017b). The current collection and recycling rate of spent LIBs from consumer electronics in China and the US is reported to be likely lower than 10%, or probably even lower than 5% (Gu et al., 2017). While the global collection rate of EV batteries is higher, at around 40-60%, the recycling of lithium is low due to economic reasons (primary production is cheaper than recycling) and, generally, other elements than lithium contained in batteries are targeted by recycling processes (Bobba et al., 2019; Harper et al., 2019; Ziemann et al., 2018). Based on this evidence, we estimate a 5% EoL-RR | Per sector; please refer to Supplementary Data |

for LIBs, which is applied to both types of batteries. The collection yield for the lithium content in batteries is calculated considering the reported 85% remelting yield, resulting in a collection and sorting yield of 6% for LIBs.

There are a number of important on-going projects aiming to improve the installed recycling capacity for lithium batteries (Harper et al., 2019), and the recycling of batteries deserve special attention if ever it is attempted to establish prospective scenarios.

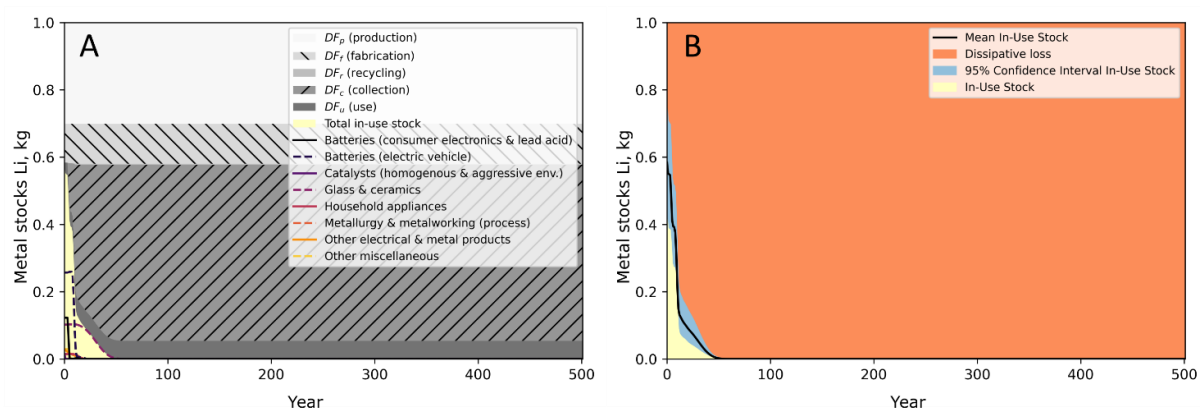


Figure B3. In-use stocks and losses of lithium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.2 Beryllium

Table B11. Beryllium.

| Beryllium | Be, element number 4 | Uncertainty | | | | | | | | | | | | |
|--|---|---|-----|-------------|-----|----------------------|-----|--|-----|-------------------|-----|-----------|-----|---|
| End-uses | <p>It is difficult to dissociate between beryllium end-uses as there is significant overlap between beryllium-containing materials and end-use sectors (Trueman and Sabey, 2014). For instance, beryllium-copper alloys represent about 80% of uses of beryllium (BeST, 2016) and are used in multiple electronic applications, in transport and aerospace for both commercial and defense applications, telecommunication, etc. Moreover, end-uses are sometimes reported as aggregated end-use sectors, e.g. aerospace and defense altogether.</p> <p>The global end-use values are estimated based on US values for years 2015 to 2019 (Lederer et al., 2016; USGS, 2020) and Europe values reported as averages for years 2012 to 2016 (European Commission, 2020a). Since the US production is the most important worldwide (around 60% of the production in 2019 and Europe is mostly dependent on imports (European Commission, 2020a), more weight was given to US end-use statistics than to Europe’s statistics when an important mismatch was observed. US is also an important manufacturer of beryllium materials and products. Given that uses have been quite constant in the past years, data are also checked against 2007 end-use distribution reported by Christmann et al. (2010) for consistency. Data matching and reconciliation into end-use sectors was performed with the available information. Auto electronics and auto components were aggregated into the transport category. Industrial applications are classified into the mechanical eq. category. Defense includes some nuclear uses, missiles, ceramic and beryllium alloy components for aerospace and military jets. These were classified in Other industrial, military & energy applications. Medical applications include high-resolution medical radiography used in computerized tomography scanning and mammography (European Commission, 2020a) and were also classified as Other industrial, military & energy applications. Energy applications are various, including research for fusion reactors. If ever fusion energy becomes widely used, demand for pure beryllium metal could grow substantially in the future (Christmann et al., 2010). The distribution of beryllium end-uses are estimated to be representative of the global yearly averages from 2015 to 2019:</p> <table><tr><td>Aviation</td><td>10%</td></tr><tr><td>Electronics</td><td>15%</td></tr><tr><td>Mechanical equipment</td><td>15%</td></tr><tr><td>Other industrial, military & energy applications</td><td>22%</td></tr><tr><td>Telecommunication</td><td>12%</td></tr><tr><td>Transport</td><td>26%</td></tr></table> | Aviation | 10% | Electronics | 15% | Mechanical equipment | 15% | Other industrial, military & energy applications | 22% | Telecommunication | 12% | Transport | 26% | U1: 2 U2: 1 U3: 2 U4: 3 U5: 1 |
| Aviation | 10% | | | | | | | | | | | | | |
| Electronics | 15% | | | | | | | | | | | | | |
| Mechanical equipment | 15% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 22% | | | | | | | | | | | | | |
| Telecommunication | 12% | | | | | | | | | | | | | |
| Transport | 26% | | | | | | | | | | | | | |
| Production yield | About 87% of the beryllium content of bertrandite and beryl ores is estimated for the recovered in the US, whose production represent over 50% of the global production (Lederer et al., 2016). US is the leading | U1: 2 U2: 2 U3: 3 U4: 3 U5: 1 | | | | | | | | | | | | |

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| | <p>producer of beryllium, although Kazakhstan also had important stockpiles of beryllium concentrates as leftovers from the Soviet Union stocks accumulated during the Cold War. However, little is known on the former Soviet Union production of beryllium concentrates, and these stockpiles are thought to be nearly depleted (Lederer et al., 2016). Hence, US production is assumed to be reasonably representative of the current production.</p> | |
| Fabrication and manufacturing | <p>The major US beryllium producer, Materion (as mentioned by the USGS, 2020), has a highly integrated production chain from beryllium ores to material (ceramics & alloys) and products manufacturing (Materion, 2016). Manufacturing losses for copper alloys (the most important material use, with approximately 80% of total beryllium consumption) can be expected to be minimal (BeST, 2016).</p> <p>Beryllium is difficult to cut and manufacture due to its high hardness, which results in a lot of new scrap being generated in some industries like aerospace (Trueman and Sabey, 2014). However, this new scrap is mostly collected and sent back to produce new alloys, since beryllium is a valuable and its recycling provides great energy savings (European Commission, 2017a; SCREEN, 2018).</p> <p>United States have historically been a major producer of beryllium bearing materials and products. The USGS static MFA for the year 2000 is used to estimate process yields for beryllium (Cunningham, 2004). It is expected to be fairly representative of global yields, as 455 tons of primary and secondary beryllium were processed within the US that year (higher volumes than global production for recent years reported by the USGS (Lederer et al., 2016; USGS, 2020)), and about 75% beryllium was used in copper alloys, similar to its current share. The calculated fabrication and manufacturing yield is of 92% (385/420 tons).</p> | <p>U1: 2 U2: 4 U3: 3 U4: 1 U5: 1</p> |
| New scrap recovery | <p>86%, calculated from (Cunningham, 2004). A lot of beryllium bearing scraps are generated in Europe (about 50% of Europe's consumption) that is sent back to recyclers outside of Europe (European Commission, 2020a).</p> | <p>U1: 2 U2: 4 U3: 3 U4: 1 U5: 1</p> |
| Remelting | <p>It is assumed that recovered new scraps are mostly from copper alloys and remelted with a 100% yield (BeST, 2016). The same yield is assumed to apply to old scraps, which are considered to be only targeted for the beryllium content when they are collected in specific high beryllium-content waste flows. Cf. explanation for fabrication and manufacturing above.</p> | <p>U1: 3 U2: 1 U3: 1 U4: 3 U5: 1</p> |
| Dissipation in use | <p>USGS reports some dissipative uses without specification on which of beryllium's applications are considered as dissipated (Cunningham, 2004). Uses in defensive military applications or space have potential for dissipation in use; however, the actual use rate for these applications could not be determined. Therefore, no dissipative uses were reported for beryllium. These are considered to be indirectly taken into account in the low collection and recycling rates reported for most applications.</p> | <p>Per sector; please refer to Supplementary Data</p> |

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| Collection and sorting | <p>Bulk metal with high beryllium content could be recycled, but it is difficult to recover as it is used in small components and represent a tiny fraction of the appliances sent to recycling (European Commission, 2020a; Lederer et al., 2016; Trueman and Sabey, 2014). It is thought that beryllium contained in copper alloys is typically non functionally recycled or lost to slag (UNEP, 2011). A global EOL-RIR of 19% was reported in the 2010 criticality European study according to Christmann et al. (2010), while no EOL recycling was reported in the 2020 study (European Commission, 2020a).</p> <p>Yet, specific recycling schemes such as those promoted by Materion might allow for the recycling of some EoL beryllium applications. Trueman and Sabey (2014) mention that pure beryllium metal applications that return to the recycling flow can easily be recycled, although this might not be the case for some space, nuclear or military applications due to contamination or their sensitive nature. In 2000, 3.8% of old scraps of beryllium were recycled in the US (Cunningham, 2004). Without further indications, we assume this collection rate only to globally apply to the industrial, aviation and transport sectors, assuming that they are the most readily recyclable sources of beryllium contained in EOL products.</p> | <p>Per sector; please refer to Supplementary Data</p> |
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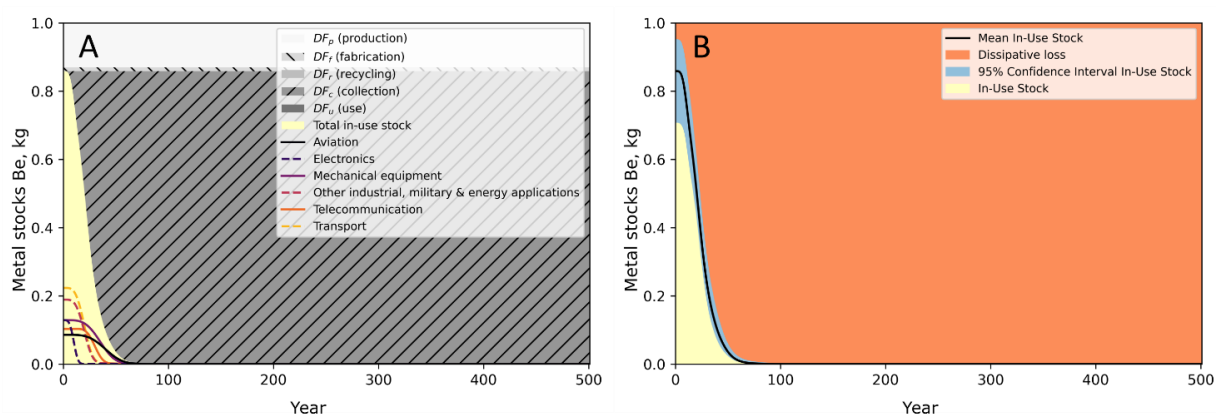


Figure B4. In-use stocks and losses of beryllium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.3 Boron**Table B12. Boron.**

| Boron | B, element number 5 | Uncertainty | | | | | | | | | | | | | | |
|--|---|---|----|------------------|----|--------------|-----|------------------|-----|--|-----|---------------------|-----|-----------------------------|----|---|
| End-uses | <p>Boron is used in over 300 applications; more than three-quarters of world consumption was estimated to be used in detergents, fertilizers, ceramics and glass in 2019 (USGS, 2020). The only global end-use distribution of boron that was found is that of Graedel et al. (2015), which provides highly aggregated end-uses for the year 2007 based on Roskill (2010). Regional end-use data are also available for Europe for years 2012-2016 (European Commission, 2020a), while historical use statistics in the US are reported until 2003 (USGS, 2015). The European data suggest that 49% of boron was used in glass products, 15% in frits and ceramics, 13% in fertilizers, 4% in chemical manufacture, 4% in metals and 11% in other uses (European Commission, 2020a). The USGS historical stats suggest that approximately 5/6th of glass uses are used for cellulosic insulation and insulation-grade glass, and the other 1/6th into other glass products in the US between 1998 to 2003 (USGS, 2015). These uses have been fairly constant from 1998 to 2003 and are assumed to be representative of the US consumption partly considered to elaborate this dataset.</p> <p>Based on these two regional distributions, the distribution for 2007 is slightly revised. The 64% share of boron used in glass products, as reported by Graedel et al. (2015), is further disaggregated. Insulation and insulation-grade glass are considered to be used in the construction sector, while other glass products are classified in the glass & ceramics sector. It is also assumed that metal uses for boron in Europe are representative for global end use, with 4% of its global share. The latter are aggregated in the alloys & solders category. Finally, other boron end-uses are split even between Other miscellaneous and Other industrial, military & energy applications to reflect the diversity of potential applications (cf. Graedel et al., 2015). The following estimates for the end-uses of boron are assumed to be representative global yearly averages for years circa 2005-2015:</p> <table><tr><td>Agricultural & environmental applications</td><td>6%</td></tr><tr><td>Alloys & solders</td><td>4%</td></tr><tr><td>Construction</td><td>49%</td></tr><tr><td>Glass & ceramics</td><td>18%</td></tr><tr><td>Other industrial, military & energy applications</td><td>10%</td></tr><tr><td>Other miscellaneous</td><td>10%</td></tr><tr><td>Other punctual applications</td><td>4%</td></tr></table> | Agricultural & environmental applications | 6% | Alloys & solders | 4% | Construction | 49% | Glass & ceramics | 18% | Other industrial, military & energy applications | 10% | Other miscellaneous | 10% | Other punctual applications | 4% | U1: 3 U2: 3 U3: 1 U4: 2 U5: 2 |
| Agricultural & environmental applications | 6% | | | | | | | | | | | | | | | |
| Alloys & solders | 4% | | | | | | | | | | | | | | | |
| Construction | 49% | | | | | | | | | | | | | | | |
| Glass & ceramics | 18% | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 10% | | | | | | | | | | | | | | | |
| Other miscellaneous | 10% | | | | | | | | | | | | | | | |
| Other punctual applications | 4% | | | | | | | | | | | | | | | |
| Production yield | <p>Graedel et al. (2015) reported a recovery rate of 80% for the combined mining and refining operations. Althaus et al. (2007) assumed a 80% extraction yield, as well as a yield of 98% for refining from sodium borates to anhydrous borax (based on US production), and of 95% for the refining of calcium borates to boric acid. Based on this information, we consider an extraction yield of 80%, and an average refining yield of 97%, resulting in a production yield of 78%. It should be noted that both references seem to refer to the extraction of boron from minerals, and not from brines.</p> | U1: 3 U2: 3 U3: 3 U4: 2 U5: 1 | | | | | | | | | | | | | | |

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| Fabrication and manufacturing | A large diversity of different products is manufactured with borates. An assumption of 95% overall yield is used in the dataset, including the potential recovery of new scrap, if ever it occurs. | U1: 4 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | The recovery of new scraps, if any, is considered to be included in the fabrication yield, and a yield of 0% is reported. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | There is no recycling considered in this dataset, and a remelting yield of 0% is reported. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | Agricultural products, as well as other punctual application (soaps and detergents) are estimated to be completely dissipated during use (type A). Other uses are considered not to be dissipative. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Some uses as a fertilizer could be considered as recycling (e.g., via composting of food waste). Nonetheless, we consider an EOL-RR of 0% for all applications based on European Commission (2020a) and Graedel et al. (2015). | Per sector; please refer to Supplementary Data |

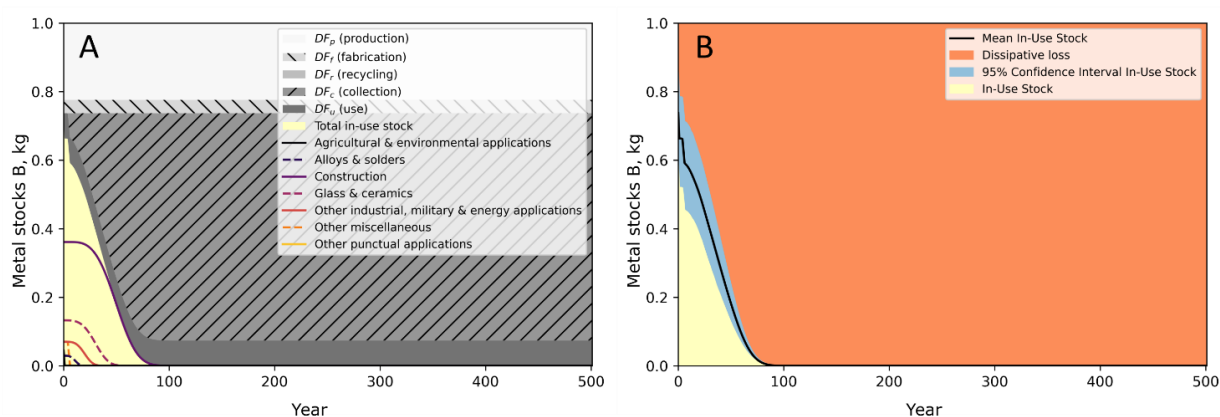


Figure B5. In-use stocks and losses of boron over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.4 Magnesium

Table B13. Magnesium.

| Magnesium | Mg, element number 12 | Uncertainty | | | | | | | | | | | | | | | | |
|--|--|---|-----|-----------|----|--------------|-----|-------------------------------------|----|--|----|-----------|----|--------------|-----|-----------|----|---|
| End-uses | <p>Most of global magnesium uses are directly from magnesium compounds or minerals such as magnesite, especially for steel refractories, while magnesium metal only represents a small share of total uses (Kramer, 2000). Graedel et al. (2015) reports end-uses for year 2002 based on Roskill (2005). The data from Graedel et al. (2015) are updated based on global data use for magnesium compounds in 2017 (Wietlisbach, 2018) as well as global end-uses for magnesium metal for years 2012-2016 reported in European Commission’s criticality study (European Commission, 2020a). The end-use of magnesium metal was considered to represent 6% of total magnesium consumption based on reported production of 1 100 and 28 000 thousand tons of magnesium metal and magnesium compounds (MgO), respectively, in 2019 (USGS, 2020). Therefore, the distribution for Mg metal of the European Commission (2020a) is normalized to a total of 6% of global magnesium consumption, and the remaining 94% is split between magnesium compound uses based on the other cited literature.</p> <p>The use of magnesium for the desulphurization of steel is considered to be dissipation in use of type B (cf. section B.1.4), and added to the metallurgy & metalworking (process) category. Environmental applications and agricultural products are aggregated altogether. The use of magnesium in iron and steel foundries, as well as magnesium metal castings, are aggregated in the transport category following the works of Graedel et al. (2015), as it is considered to be the main use for the produced materials (e.g., ductile iron).</p> <p>Based on the consulted literature, the remainder of other uses are thought to mostly include various industrial tools and machinery, and structural uses. Therefore, they are included in the Other industrial applications category. The following distribution for magnesium end-uses is estimated to be representative of the global yearly average for years circa 2017:</p> <table> <tr> <td>Agricultural & environmental applications</td> <td>15%</td> </tr> <tr> <td>Chemicals</td> <td>6%</td> </tr> <tr> <td>Construction</td> <td>17%</td> </tr> <tr> <td>Metallurgy & metalworking (process)</td> <td>1%</td> </tr> <tr> <td>Other industrial, military & energy applications</td> <td>4%</td> </tr> <tr> <td>Packaging</td> <td>1%</td> </tr> <tr> <td>Refractories</td> <td>53%</td> </tr> <tr> <td>Transport</td> <td>3%</td> </tr> </table> | Agricultural & environmental applications | 15% | Chemicals | 6% | Construction | 17% | Metallurgy & metalworking (process) | 1% | Other industrial, military & energy applications | 4% | Packaging | 1% | Refractories | 53% | Transport | 3% | U1: 2 U2: 2 U3: 1 U4: 2 U5: 1 |
| Agricultural & environmental applications | 15% | | | | | | | | | | | | | | | | | |
| Chemicals | 6% | | | | | | | | | | | | | | | | | |
| Construction | 17% | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 1% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 4% | | | | | | | | | | | | | | | | | |
| Packaging | 1% | | | | | | | | | | | | | | | | | |
| Refractories | 53% | | | | | | | | | | | | | | | | | |
| Transport | 3% | | | | | | | | | | | | | | | | | |
| Production yield | <p>Graedel et al. (2015) reported extraction losses of 28.5% and other pre-fabrication losses of 5%. However, this is reportedly for magnesite production from dolomite based on Ramakrishnan and Koltun (2004). Yet, dolomite represents only a small share of global production in</p> | U1: 3 U2: 2 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | | | | | |

| | | |
|--------------------------------------|--|---|
| | comparison to other minerals such as magnesite, representing about 84% of total production (Wietlisbach, 2018). Harraz (2017) presents a yield of 0.75 ton of electrofused MgO for an input of 2.5 tons of magnesite ore mined, suggesting a production yield of about 63%. Based on this information, we estimate an average production yield of 65% across all potential magnesium production routes. | |
| Fabrication and manufacturing | Scarce information could be found on the fabrication and manufacturing yield of magnesium-containing products. The USGS statistics suggest a manufacturing yield of 92% for magnesium metal products in 1998, with a new scrap recovery rate of 86% (USGS, 2004b). However, as noted previously, this covers only 6% of the end-uses of magnesium. Therefore, it is attempted to estimate the fabrication yield for refractories, as they are by far the largest end-use for magnesium. Yet, no information on the yield of the manufacturing processes for refractories could be found. Still, the manufacturing process is well described by the US EPA (2003). Based on that reference, we assume that about 5-10% of magnesium could be emitted as particulate matter, or be lost as a residue of the crushing, grinding, calcining and milling processes. Furthermore, we assume that few efforts would be made to recycle these new scraps given the low economic value of magnesia. Based on this information, we estimate an overall fabrication and manufacturing yield of 92.5% for all of magnesium products, including the recovery of new scraps, whenever it occurs. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | The recovery of new scraps, if any, is considered to be included in the fabrication yield, and a yield of 0% is reported. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | 95% (assumption) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | Some sources consider magnesium use in refractories as a dissipative use (Bell et al., 2017; Wang et al., 2018), while recycling rates ranging from 15 to 90% have been reported (Muñoz et al., 2020). However, these rates include non-functional recycling in road bed aggregates or as slag former and conditioners in metallurgical processes (Horckmans et al., 2019). Here, we assume the use in refractories not to be dissipative, as for magchrome refractories (Ciacci et al., 2015). Agricultural and environmental applications are considered to be completely dissipated during use (type A). The metallurgical use of Mg compounds to desulfurize steel is considered to be dissipative (type B). Likewise, other magnesium chemicals are assumed to be dissipated during use (type B) based on their most common applications, such as magnesium hydroxide used for flue gas desulfurization and water treatment, or magnesium sulfate used as food additive and pharmaceuticals (Kramer, 2000; Wietlisbach, 2018). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Graedel et al. (2015) reported EOL-RRs of 60% for packaging, and 75% for magnesium metal used in transport and construction, using aluminium used in similar applications as proxies. Similarly, we assume the collection rates of aluminium packaging to represent those of magnesium used in the same application, and report a collection yield of | Per sector; please refer to Supplementary Data |

| | | |
|--|---|--|
| | <p>58% for packaging. The collection yields for iron applications are used as proxies to estimate those of magnesium used in similar applications, which are also almost identical to those of aluminum for these two sectors: 93% for transport, and 87% for construction. The latter is corrected to take the share of Mg metal included in the construction sector into account (approximately 4%).</p> <p>Establishing the functional recycling rate of magnesium minerals used in refractories and construction sectors is not straightforward. Since primary magnesite can be used to produce construction materials such as cement, we consider that some of the recycled refractories used for cement production actually offset the demand for primary magnesite, thereby potentially consisting in functional recycling. As a first estimate, an EoL-RR of 10% of refractories is considered. Moreover, some magnesium compounds are directly used in construction materials, which are thought to be mostly cement (Kramer, 2000; Wietlisbach, 2018). However, we did not consider the recycling of cement to be functional, based on the works of Gutowski et al. (2013); and a collection yield of 0% is reported for this application. As magnesium metal represents only 4% of the use of magnesium in construction applications, a collection yield of 3% is reported for that sector. Finally, EoL-RR of 0% are considered for other end-uses (Graedel et al., 2015). The collection yields are corrected accordingly with the reported remelting yield of 95%.</p> <p>We would like to highlight that increasing quantities of magnesium are reported to be obtained from seawater, thereby making the anthropogenic cycle of magnesium potentially include the environmental media. It was not investigated how the environmental applications of magnesium and emissions to the environment could be considered to be somewhat recyclable from brine.</p> | |
|--|---|--|

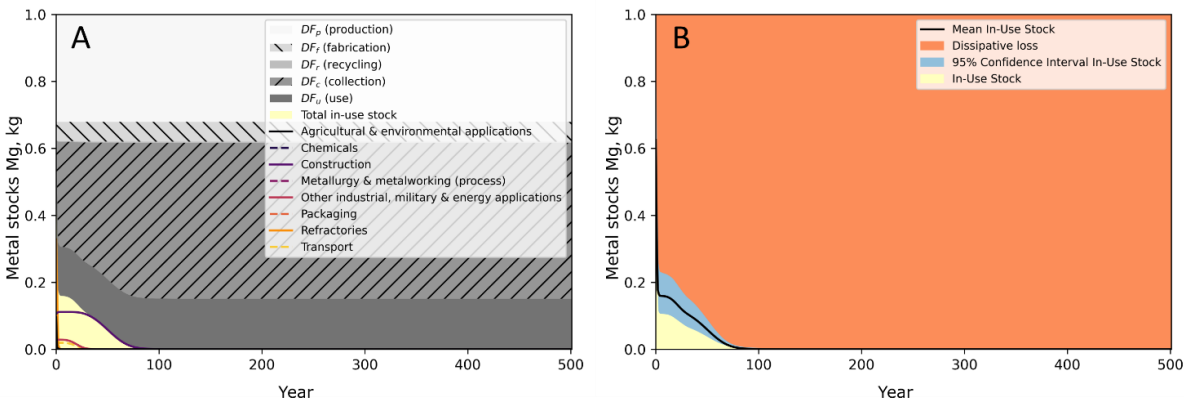


Figure B6. In-use stocks and losses of magnesium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.5 Aluminium

Table B14. Aluminium.

| Aluminium | Al, element number 13 | Uncertainty | | | | | | | | | | | | | | | | |
|--|--|---|-----|----------------------|----|----------------|-----|----------------------|----|-------------------------------------|----|--|----|-----------|-----|-----------|-----|---|
| End-uses | <p>Global end-use distribution are available for year 2007 (Graedel et al., 2013), 2014 (Bertram et al., 2017) and 2015 (USITC, 2017). The most recent distribution of wrought aluminium products is considered (USITC, 2017). Aluminum foil was aggregated along with packaging applications. Aluminum use in electrical sector was classified in infrastructure, as major applications include medium- and high-voltage overhead power lines as well as aluminum alloy wiring in the construction of new buildings (USITC, 2017). Moreover, about 3% of aluminum is used to deoxidize steel and lost to slags (Ciacci et al., 2015), corresponding to the destructive use reported by other authors (Bertram et al., 2017; Liu et al., 2013). This percentage is assumed to remain relatively constant as both aluminium and steel are consistently and widely used. Therefore, 3% of aluminium is reported to be used for metallurgical processes, and the remaining end-uses are normalized to fit a total of 97% accordingly.</p> <p>The global end-use distribution for aluminium is the following:</p> <table><tr><td>Construction</td><td>33%</td></tr><tr><td>Household appliances</td><td>4%</td></tr><tr><td>Infrastructure</td><td>17%</td></tr><tr><td>Mechanical equipment</td><td>9%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>3%</td></tr><tr><td>Other industrial, military & energy applications</td><td>2%</td></tr><tr><td>Packaging</td><td>20%</td></tr><tr><td>Transport</td><td>12%</td></tr></table> | Construction | 33% | Household appliances | 4% | Infrastructure | 17% | Mechanical equipment | 9% | Metallurgy & metalworking (process) | 3% | Other industrial, military & energy applications | 2% | Packaging | 20% | Transport | 12% | U1: 2 U2: 2 U3: 1 U4: 2 U5: 1 |
| Construction | 33% | | | | | | | | | | | | | | | | | |
| Household appliances | 4% | | | | | | | | | | | | | | | | | |
| Infrastructure | 17% | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 9% | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 3% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 2% | | | | | | | | | | | | | | | | | |
| Packaging | 20% | | | | | | | | | | | | | | | | | |
| Transport | 12% | | | | | | | | | | | | | | | | | |
| Production yield | 88% (Helbig et al., 2020, based on Bertram et al., 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 59% (Helbig et al., 2020, based on Bertram et al., 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| New scrap recovery | 95% (Helbig et al., 2020, based on Bertram et al., 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Remelting | 97% (Helbig et al., 2020, based on Bertram et al., 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Dissipation in use | 0% for all applications except metallurgy, for which 100% dissipation in use is considered (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | |

| | | |
|-------------------------------|---|---|
| Collection and sorting | <p>Helbig et al., (2020) calculated an average 83% collection yield based on Bertram et al. (2017). The latter article was written in parts by authors affiliated to the International Aluminium Institute.</p> <p>The worldwide market weighted recycling rates reported in the Global Material Flow model of the (International Aluminium Institute, 2018) are used to calculate application-specific collection yields. While more recent estimates are reported in that reference, we considered the recycling yields of 2014 to be consistent with the reference year of the study of (Bertram et al., 2017). For the aggregated packaging and foil sectors, the weighted average is calculated based on end-use demand in 2014 established by the (International Aluminium Institute, 2018). Considering the remelting yield of 97%, the following collection yields are calculated: Construction, 87%, Infrastructure, 68%, Transport, 93%, Packaging, 58%; Mechanical equipment, 67%; Household appliances, 58%; and Other industrial, military & energy applications, 45%.</p> | <p>Per sector; please refer to Supplementary Data</p> |
|-------------------------------|---|---|

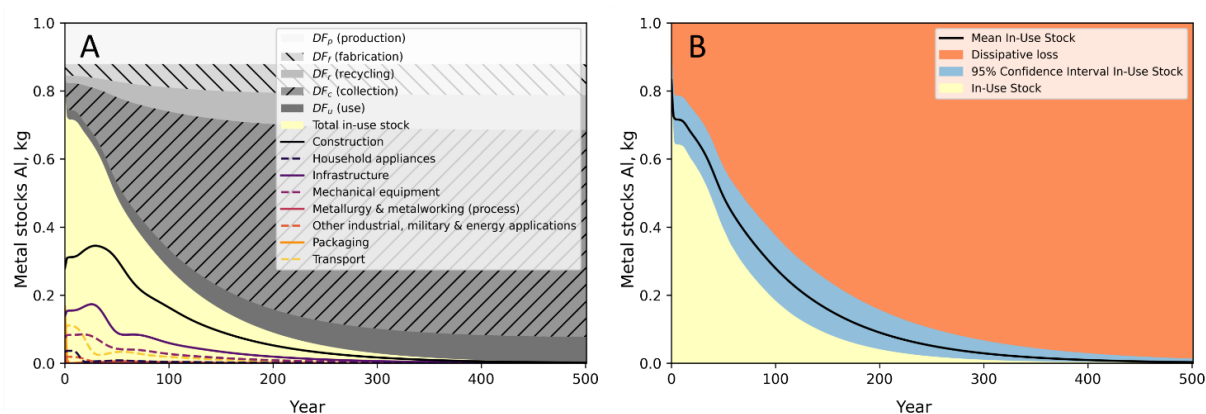


Figure B7. In-use stocks and losses of aluminium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.6 Silicon

Note: Since silicon is the second most common element in the earth's crust after oxygen, it is expected that enormous amounts of silicon are extracted from the ground yearly. It notably a constituent of quartz crystals and silica sand which are used in a range of applications (European Commission, 2020c), albeit not for the specific characteristics of silicon metal. For such reasons, it is treated separately from silica sand in criticality studies (BRGM, 2019a; European Commission, 2020c). Therefore, we only consider the production of silicon metal from high purity quartz that is used for silicon metal production. The metallurgical use of ferrosilicon or calcium silicon for e.g. the deoxidization or reduction of steel, magnesium or nickel is not covered.

Table B15. Silicon.

| Silicon | Si, element number 14 | Uncertainty |
|-----------------|--|--|
| End-uses | <p>Global end-uses of silicon are reported for 2018 (BRGM, 2019a). Another estimate is reported by the European Commission (2020a), suggesting that around 50% of silicon metal is used in silicones, 40% in aluminium, and 10% in solar panels. Another end-use distribution could be calculated for 1998 based on Williams (2003). Finally, a partial distribution of electronic grade silicon can be calculated for solar cells and wafers in 2009 (Takiguchi, 2011). The BRGM's values are considered to build the present dataset, and some refinements are made based on other available information, as detailed below.</p> <p>The BRGM reports that 41% of silicon is used as an alloying element in aluminium, iron and steel product (mostly aluminium); 35%, in silicones and silanes; 18% in solar cells; and 6% in other uses (BRGM, 2019a). Between 0.4% and 1% of Si is added to almost all aluminium alloys, and high temperature applications may contain up to 13% Si (Maubert, 1989). An important fraction of silanes may be used as precursors for the manufacture of optical fibers and semi-conducting wafers or for the production of polysilicon, further used in the manufacture of wafers (Williams, 2003). Based on the available information, it is estimated that around 2% of global silicon (as silanes) is used to produce semiconducting wafers and fiber optic cables (both were aggregated in electronics); and the remainder 33% of the silanes and silicone category is estimated to be used for silicone applications.</p> <p>Given the variety of applications for aluminium-silicon alloys (mostly cast products), they are included in the alloy category. The family of silicones include oils, pastes, emulsions, resins, gums and elastomers that are used in over 200 sectors (Maubert, 1989). These applications include inherently dissipative uses such as lubricating greases, and non-dissipative uses such as silicone rubber and elastomeric seals, and resins used for isolation purposes in electronics (Maubert, 1989). Likewise, other silicon compounds uses are thought to be used in a range of applications such as food additives, cosmetics, thermocouples, crucibles, refractories, ceramics, etc., while other silicon alloys include brass used in e.g. shipbuilding and nickel-silicon alloys used in e.g. electronics and chemical industries (Maubert, 1989). Without further information, we roughly split silicone applications and "other" silicon uses evenly between Other industrial, military & energy applications, Other</p> | <p>U1: 2 U2: 1 U3: 1 U4: 2 U5: 2</p> |

| | | | | | | | | | | | | | | |
|--|---|---|-----|-------------|----|--|-----|---------------------|-----|-----------------------------|-----|-------------|-----|--|
| | <p>miscellaneous and Other punctual applications. The following end-use distribution is estimated to be representative of global end-uses of silicon metal in 2018:</p> <table><tr><td>Alloys & solders</td><td>41%</td></tr><tr><td>Electronics</td><td>2%</td></tr><tr><td>Other industrial, military & energy applications</td><td>13%</td></tr><tr><td>Other miscellaneous</td><td>13%</td></tr><tr><td>Other punctual applications</td><td>13%</td></tr><tr><td>Solar cells</td><td>18%</td></tr></table> <p>Although this distribution is quite generic due to the lack of precise information available, it is estimated to represent the large diversity of lifetimes amongst the various silicon uses reasonably well. Nonetheless, it may warrant additional investigations of the silicon anthropogenic cycle.</p> | Alloys & solders | 41% | Electronics | 2% | Other industrial, military & energy applications | 13% | Other miscellaneous | 13% | Other punctual applications | 13% | Solar cells | 18% | |
| Alloys & solders | 41% | | | | | | | | | | | | | |
| Electronics | 2% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 13% | | | | | | | | | | | | | |
| Other miscellaneous | 13% | | | | | | | | | | | | | |
| Other punctual applications | 13% | | | | | | | | | | | | | |
| Solar cells | 18% | | | | | | | | | | | | | |
| Production yield | The production yield of silicon metal from quartz is estimated to be of around 85% in a well-operated furnace (Ali et al., 2018), and a production yield of 80% is estimated including losses to other processes and mining losses. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | The fabrication and manufacturing processes for metallurgical grade silicon are thought to have a globally high yield, since process residues (e.g., kerf loss) and off-grade silicon can still be used in solar cell manufacturing and as a cheap additive to aluminium alloys (Takiguchi, 2011; Williams, 2003). We assume the yield of fabrication and manufacturing processes for chemical grade silicon (used in the manufacture of silanes and silicones) to also be similarly efficient. A global yield of 90% is reported for silicon-containing products, including the recovery of new scraps that are used in other applications requiring primary silicon metal. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |
| New scrap recovery | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | |
| Remelting | The remelting of new scraps is considered to be included in the fabrication and manufacturing yield. No uses of silicon are thought to be functionally recycled currently (BRGM, 2019a; CRM Alliance, n.d.; European Commission, 2020a), and a remelting yield of 0% is reported. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | |
| Dissipation in use | Most uses of silicon are estimated not to be dissipative as they are expected to be mostly used in protected environments. Some silicone products are reported as punctual applications for which a dissipation in use of 100% is reported, including e.g. lubricating oils and food additives. | Per sector; please refer to Supplementary Data | | | | | | | | | | | | |
| Collection and sorting | No uses of silicon are thought to be functionally recycled currently (BRGM, 2019a; CRM Alliance, n.d.; European Commission, 2020a), and a collection yield of 0% is reported. | Per sector; please refer to Supplementary Data | | | | | | | | | | | | |

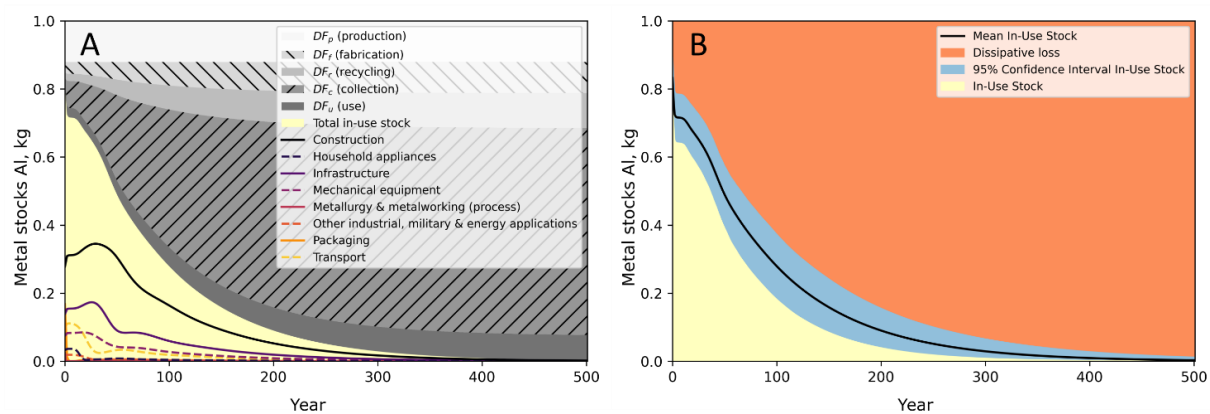


Figure B8. In-use stocks and losses of silicon over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.7 Scandium

Table B16. Scandium.

| Scandium | Sc, element number 21 | Uncertainty | | | | | | |
|-----------------------------------|---|---|----|-----------------------------------|----|------------------------|-----|---|
| End uses | <p>The global distribution of scandium into end-uses is available for years 2008 (Graedel et al., 2013) and 2017 (BRGM, 2017c). In recent years, its dominant application has been in solid oxide fuel cells, followed by scandium-aluminium alloys (BRGM, 2017c). Alloys are used for high performance applications such as sporting goods and aerospace; other uses include ceramics, electronics, lasers, lighting, and radioactive isotope (USGS, 2020). We assume that half of the scandium alloys are used in aerospace applications, while the remainder is classified as other metal products. The following distribution is representative of end-uses of scandium in 2017, based on BRGM (2017c):</p> <table><tr><td>Aviation</td><td>5%</td></tr><tr><td>Other electrical & metal products</td><td>5%</td></tr><tr><td>Solid oxide fuel cells</td><td>90%</td></tr></table> | Aviation | 5% | Other electrical & metal products | 5% | Solid oxide fuel cells | 90% | U1: 2 U2: 1 U3: 1 U4: 3 U5: 3 |
| Aviation | 5% | | | | | | | |
| Other electrical & metal products | 5% | | | | | | | |
| Solid oxide fuel cells | 90% | | | | | | | |
| Production yield | <p>Only about 10-15 tons of scandium is produced annually (BRGM, 2017c; USGS, 2019). Scandium is highly dispersed in the crust due to the absence of geological processes concentrating it (Emsley, 2014). It has typically been obtained as a by-product of REE, uranium or nickel-cobalt lateritic ores, as well as from solid residues from tungsten, titanium or bauxite processing (BRGM, 2017c). The weathering of lateritic deposits developed over ultramafic–mafic rocks was found to enrich scandium concentrations by a factor of ten in Eastern Australia deposits, which could make such deposits a viable source of primary scandium (Chassé et al., 2017).</p> <p>It is uneasy to estimate what portion of scandium should be considered as a resource, and therefore what is the actual production yield. Panousi et al. (2016) estimated a production yield of 85% based on the voluntary production of scandium from a few select processes or projects as described by Wang et al. (2011) and Khoo (2012). However, much more scandium that is extracted could be processed as a by-product and be considered as a resource, and therefore we expect the actual production yield, as defined in this Annex, to be lower.</p> <p>There seems to be some degree of anticipation of an important increase yearly demand for scandium, especially for aluminium-scandium alloys for casting and additive manufacturing. There are multiple on-going projects aiming to recover scandium as a by-product of uranium, bauxite, nickel and cobalt ores (Khoo, 2012; USGS, 2019), or from past mining wastes, e.g. from red mud caustic wastes, uranium tailings, coal and coal by-products, and sulfate titanium wastes (European Commission, 2020a; USGS, 2019).</p> <p>As a first estimate, we estimate the amount of scandium potentially lost to red mud waste, assuming that all of the scandium content of red mud could be considered as a resource. Indeed, Wang et al. (2011) noted that ores with</p> | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 | | | | | | |

| | | |
|--------------------------------------|---|---|
| | <p>a scandium content ranging between 0.002 and 0.005% can be considered as resources of scandium and deserve exploitation. An estimated 0.0078 wt.% of Sc_2O_3 has been measured to be present in red mud by Wei et al. (2020), while Khairul et al. (2019) mention values ranging between 60 and 120 mg of scandium per kg of red mud. These references suggest a content of 0.005 wt.% and 0.006 – 0.012 wt.% of scandium in red mud, respectively, and therefore the scandium content of red mud may potentially be considered as a resource.</p> <p>Considering that about 150 million tons of red mud is generated yearly (Khairul et al., 2019), it is estimated that between 8 000 and 18 000 tons of scandium are deposited as part of red mud wastes each year. Based on this, it can be estimated that the production yield of scandium from bauxite most likely ranges between 0.05 and 0.2%. An average production yield of 0.13% is proposed as a first estimate for the production yield of scandium. It may warrant further investigations, including other potential sources of scandium.</p> | |
| Fabrication and manufacturing | 95%, including the recovery of new scraps (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | While some minor applications of scandium may have a potential for dissipation (Ciacci et al., 2015), these were assumed to be negligible and a 0% rate is reported for all scandium applications. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Scandium contained in EoL products is not functionally recycled (BRGM, 2017c; Panousi et al., 2016). | Per sector; please refer to Supplementary Data |

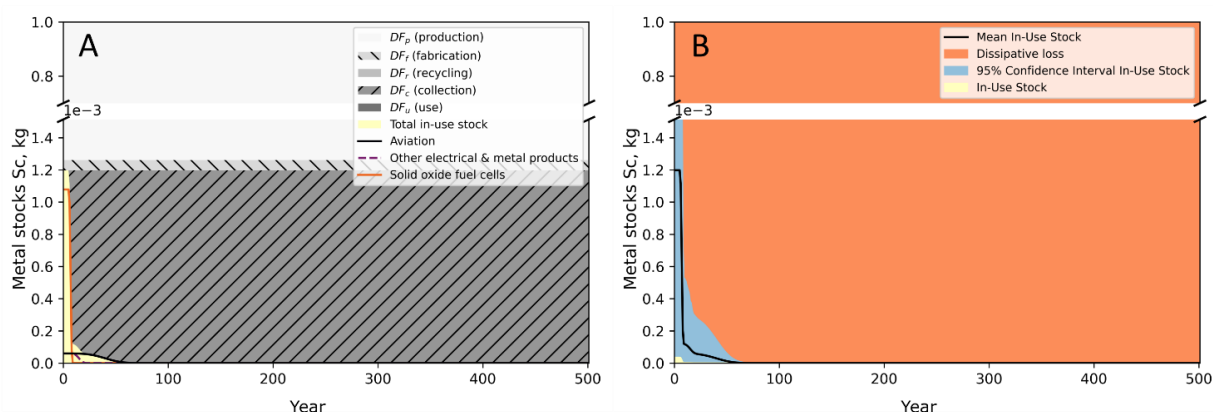


Figure B9. In-use stocks and losses of scandium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.8 Titanium**Table B17. Titanium.**

| Titanium | Ti, element number 22 | Uncertainty | | | | | | | | | | | | | | |
|--|---|---|----|--|----|---------------------|----|-------|-----|-------|-----|---------------------------|----|----------|-----|---|
| End-uses | <p>Global end-use data are reported for 2005 (Ciacci et al., 2015; Graedel et al., 2015) and 2013 (BRGM, 2017a). Titanium is mostly used as a pigment (TiO₂), with approximately 90% of global uses. These are mainly split between paint, paper, plastics & rubber, and to a lesser extent textile fibers and printing ink (BRGM, 2017a).</p> <p>This end-use distribution is based on the data for 2013 (BRGM, 2017a). Various industrial applications for titanium metal are included in the Other industrial category, which includes e.g. chemical and petrochemical plants, deep-sea petroleum production, and seawater desalination (BRGM, 2017a; European Commission, 2020a; Woodruff et al., 2017). Printing ink is classified along with pigments used by the paper industry, assuming that printing ink is used on paper and therefore has the same lifetime. Moreover, parts of miscellaneous titanium applications are thought to be inherently dissipative, such as nano-scale applications in sunscreens, toothpaste, cosmetics, food additives, etc. (BRGM, 2017a; Ciacci et al., 2015; European Commission, 2020b). We assume that 1% of titanium is used in such applications, and grouped them in the pharmaceuticals & cosmetics category.</p> <p>The following end-uses of titanium are estimated to be representative of 2013:</p> <table><tr><td>Aviation</td><td>2%</td></tr><tr><td>Other industrial, military & energy applications</td><td>8%</td></tr><tr><td>Other miscellaneous</td><td>2%</td></tr><tr><td>Paint</td><td>53%</td></tr><tr><td>Paper</td><td>11%</td></tr><tr><td>Pharmaceutics & cosmetics</td><td>1%</td></tr><tr><td>Plastics</td><td>23%</td></tr></table> | Aviation | 2% | Other industrial, military & energy applications | 8% | Other miscellaneous | 2% | Paint | 53% | Paper | 11% | Pharmaceutics & cosmetics | 1% | Plastics | 23% | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 |
| Aviation | 2% | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 8% | | | | | | | | | | | | | | | |
| Other miscellaneous | 2% | | | | | | | | | | | | | | | |
| Paint | 53% | | | | | | | | | | | | | | | |
| Paper | 11% | | | | | | | | | | | | | | | |
| Pharmaceutics & cosmetics | 1% | | | | | | | | | | | | | | | |
| Plastics | 23% | | | | | | | | | | | | | | | |
| Production yield | 86%, calculated based on the estimate for the recovery and refining of Graedel et al. (2015). | U1: 3 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | |
| Fabrication and manufacturing | As new titanium scraps from metal applications are collected and recycled efficiently (Goonan, 2010; Takeda and Okabe, 2019), and as processes required to integrate and apply pigments in different applications are assumed to be relatively efficient, we consider an overall 95% yield covering all fabrication and manufacturing routes (including in-house new scrap recycling). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | | | |
| New scrap recovery | Only does titanium metal have a potential for recycling. The major resource for titanium recycling is in-house titanium scrap (metal) generated in smelting and fabrication processes (BRGM, 2017a; Takeda et al., 2020; Takeda and Okabe, 2019). Since cascade recycling occurs, it is difficult to precisely estimate the new scrap recovery yield. Moreover, | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | |

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| | titanium metal only covers about 5% of the end-uses of titanium. Therefore, we assumed the fabrication and manufacturing process yield to include the recovery of new scraps. | |
| Remelting | 95%, assuming that remelting has the same yield as refining. | U1: 4 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | Ciacci et al. (2015) estimated that 10% uses in paint are dissipated in use due to corrosion (type B). Moreover, the uses of titanium included in the pharmaceutical & cosmetics category are estimated to be dissipative (type A). Dissipation in use for other titanium applications is considered to be negligible (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Only metal uses are currently potentially recyclable (Ciacci et al., 2015). Graedel et al. (2015) report an EOL-RR of 20% for the “other” category, which includes titanium metal applications. The estimate is based on information obtained from a report for the US. We consider this estimate to apply to the Aviation and Other industrial, military & energy applications. The reported collection yields are corrected considering the remelting yield of 95%. | Per sector; please refer to Supplementary Data |

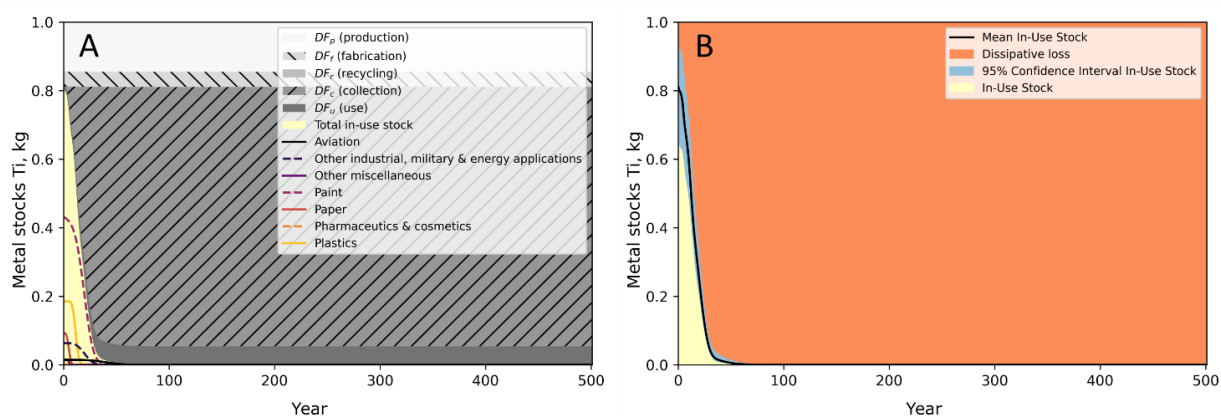


Figure B10. In-use stocks and losses of titanium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.9 Vanadium

Table B18. Vanadium.

| Vanadium | V, element number 23 | Uncertainty |
|----------------------|---|-------------------------------------|
| End uses | Over 90% of vanadium is used in steel alloys (BRGM, 2018b; Nuss et al., 2014). The other uses of vanadium include titanium alloys used in aerospace industry for e.g. airframes and jet engine parts, aluminium alloys, as well as catalysts, glasses, ceramics, electronics and redox flow batteries (BRGM, 2018b; European Commission, 2020a; Kelley et al., 2017; Nuss et al., 2014). While catalysts could be used in both heterogeneous and homogenous catalysts (Ciacci et al., 2015), their typical average lifetime is estimated to be of 8-10 years (Ciacci et al., 2015; Nuss et al., 2014), and therefore they are aggregated in the Catalysts (heterogeneous & stable env.) category. | U1: 3 |
| | | U2: 1 |
| | | U3: 1 |
| | | U4: 2 |
| | | U5: 1 |
| | Global end-uses are reported for the year 2017 (BRGM, 2018b), 2000 and 2011 (Nuss, 2014) and 2014 (Roskill, 2014). Bushveld Minerals Limited (2019) reports around 3% end-use of vanadium in redox flow batteries in 2018. Uses of vanadium are mostly reported as different types of steels in which it is alloyed (e.g., HSLA steel, full alloy steel) which are each used in different end-use sectors. Hence, classifying steels into different end-use categories is challenging. Here, it is disaggregated upon qualitative description and quantitative distribution of the most important end-uses for the different types of steels and alloys reported in a range of sources (BRGM, 2018b; Ciacci et al., 2015; European Commission, 2020a; Kelley et al., 2017; Nuss et al., 2014) as well as historical USGS stats. Based on available information, steels are considered to be used approximately 1/3 each in transport, construction (including pipelines and nuclear plants) and mechanical equipment. Although this end-use distribution would benefit from more detailed data, each of the important steel uses reported here are rather long lived, with a minimum average lifetime of 20 years. Hence, it is not expected that more precise data would have much influence on the results of this model. | |
| | Based on this information, we estimated the following end-use distribution circa 2017-2018: | |
| | Aviation | 4% |
| | Batteries (utility & industrial) | 3% |
| | Catalysts (heterogeneous & stable env.) | 2% |
| Construction | 30% | |
| Glass & ceramics | 1% | |
| Mechanical equipment | 30% | |
| Transport | 30% | |
| Production yield | Since vanadium can be produced from a wide array of materials and through specific proprietary procedures (USGS, 1994), estimating its production yield is difficult. Vanadium is mostly produced in three distinct ways: from the co-production along with iron, from primary production | U1: 3 U2: 2 U3: 2 U4: 3 U5: 2 |

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| | <p>from ores and secondary production from e.g. spent catalysts from the petroleum industry (Moskalyk and Alfantazi, 2003; Nuss et al., 2014; Zhang et al., 2014). In 2014, co-production with iron provided about 64% of total supply of vanadium, along with 24% from primary production and 12% from other sources such as spent petroleum catalysts and vanadium-uranium ores (GE21 Consultoria Mineral, 2017). While co-production with iron is the most important source of vanadium, only do the largest steel plants recover vanadium oxides from slags (Ciacci et al., 2015).</p> <p>Around 2000, South Africa was the leading producer of vanadium, followed by Russia, China and to a lesser extent US and Australia (Goonan, 2011b; Moskalyk and Alfantazi, 2003). More recently, China became the main vanadium producer with around 60% of global production in 2019, followed by South Africa, Russia and Brazil covering most of the remaining production (Roskill, 2014; USGS, 2020). Nuss et al. (2014) calculated a 13.8% production loss based on USGS (1994), which seems to cover only vanadium recovery from plants that actually aim to recover vanadium as a by-product. This loss was of 10% in 2004 (Goonan, 2011b). Similarly, GE21 Consultoria Mineral (2017) report recovery yields of approximately to 90%. However, important quantities of vanadium may be lost in other potential sources of vanadium which are not accounted for in these yields. For instance, in 2010, around 32.2% of the available vanadium from different production routes was extracted in China, with only 25.6% of the iron ores being processed for vanadium extraction (Zhang et al., 2014). Given the paucity of available data, we estimate the global production yield based on an extrapolation of US and China's contributions to global production in 2019 based on USGS (2020) and their respective yields for the most recent years for which data was available, resulting in a production yield of 33%. As only a few countries produce vanadium in comparison to those refining petroleum or producing steel, it is likely that the actual global yield from all of the potential vanadium sources would be below this value, which may warrant additional investigations.</p> | |
| Fabrication and manufacturing | <p>A few national MFAs are available for vanadium, for the US and China (USGS, 2011, 1994; Zhang et al., 2014). The fabrication and manufacturing and new scrap recovery are extrapolated from available data for China (Zhang et al., 2014) and the US (Goonan, 2011b). Based on these two static MFAs, we assume that China is representative of 89% of the global production (approximately 31.6 kt entering fabrication), and the US, 11% (4 kt entering fabrication). However, the fabrication yield is not possible to measure from the MFA of Goonan (2011b) since vanadium used by the steel industry is reported to be dissipated by default, whereas we consider such losses as dissipation of type C. Hence, we assume the same dissipative losses to molten slags during the fabrication of steel products as in China in year 2010 in the calculation (approximately 22%). The resulting yield is 68%.</p> | <p>U1: 2 U2: 3 U3: 2 U4: 3 U5: 2</p> |
| New scrap recovery | <p>1%, using the same method as for fabrication and manufacturing, based on Goonan (2011b) and Zhang et al. (2014).</p> | <p>U1: 2 U2: 3 U3: 2 U4: 3 U5: 2</p> |

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| Remelting | We assume that collected new scraps are remelted with a yield of 95%. This yield only applies to new scraps, as old scraps are considered not to be functionally recycled. | U1: 4 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | Negligible for most applications; we consider that 10% of the vanadium content of catalysts is dissipated in use, based on Ciacci et al. (2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | The functional recycling of old vanadium scraps is mostly from high speed steels and superalloys (BRGM, 2018b). Most of the vanadium used in steel is not readily recovered, with the global EoL-RR for vanadium reported as below 1% (Graedel et al., 2011). While the USGS reported that around 40% of vanadium in catalysts originates from recycled vanadium from spent chemical process catalysts in the US in 2019 (USGS, 2020), these seem to refer to vanadium that accumulated on catalysts during petroleum refining rather than from actual vanadium catalysts (Nuss et al., 2014). Moreover, it is reported that China (which is an important consumer of vanadium) virtually did not recycle any vanadium in 2010 (Zhang et al., 2014). Based on this information, we consider the functional recycling of old vanadium scraps to be globally negligible, and a collection yield of 0% is reported in the dataset. It should be noted that parts of these losses could be reported as remelting losses instead. | Per sector; please refer to Supplementary Data |

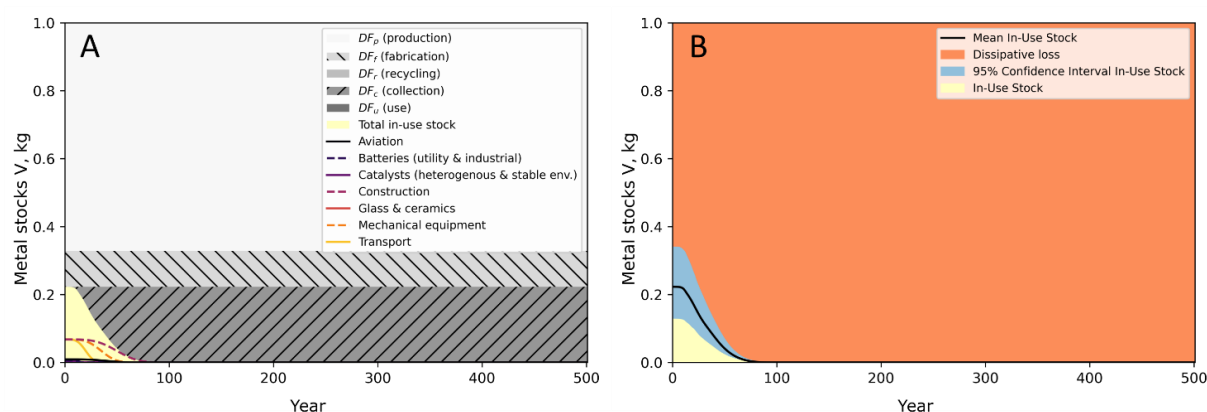


Figure B11. In-use stocks and losses of vanadium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.10 Chromium**Table B19. Chromium.**

| Chromium | Cr, element number 24 | Uncertainty | | | | | | | | | | | | | | | | | | |
|--|--|-------------------------------------|----|--------------|-----|----------------------|----|----------------|-----|----------------------|-----|-------------------------------------|----|--|-----|--------------|------|-----------|-----|---|
| End-uses | <p>Global end-use distribution of chrome are available for 2000 (Ciacci et al., 2015 based on Johnson et al., 2006) and 2015 (BRGM, 2017d). The end-use distribution for chromium is calculated based on the data of 2015 (BRGM, 2017d). Since most of the end-uses for chromium are reported as materials (e.g., 23% chromium steels) or aggregated in multiple industries (e.g., 48% of stainless steel used in food industry, medical & domestic utensils), the BRGM’s distribution is partially matched with end-use sectors using the information of Ciacci et al. (2015) as an indication. Chromite directly used as foundry sand is accounted for in the Metallurgy & metalworking (process) category; part of chromium steels is aggregated in the mechanical equipment category along with industrial equipment. Half of the chemicals are assumed to be used in CCA used for wood treatment and aggregated in the infrastructure sector. The other half is aggregated in the Other industrial, military & energy applications category due to the variety of applications it includes (pigments for paint, leather tanning, chromium metal for e.g. aerospace, and chrome plating). The following end-use distribution is estimated to be representative of the year 2015:</p> <table><tr><td>Alloys & solders</td><td>4%</td></tr><tr><td>Construction</td><td>12%</td></tr><tr><td>Household appliances</td><td>5%</td></tr><tr><td>Infrastructure</td><td>14%</td></tr><tr><td>Mechanical equipment</td><td>31%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>2%</td></tr><tr><td>Other industrial, military & energy applications</td><td>14%</td></tr><tr><td>Refractories</td><td>0.2%</td></tr><tr><td>Transport</td><td>18%</td></tr></table> | Alloys & solders | 4% | Construction | 12% | Household appliances | 5% | Infrastructure | 14% | Mechanical equipment | 31% | Metallurgy & metalworking (process) | 2% | Other industrial, military & energy applications | 14% | Refractories | 0.2% | Transport | 18% | U1: 2 U2: 2 U3: 1 U4: 2 U5: 1 |
| Alloys & solders | 4% | | | | | | | | | | | | | | | | | | | |
| Construction | 12% | | | | | | | | | | | | | | | | | | | |
| Household appliances | 5% | | | | | | | | | | | | | | | | | | | |
| Infrastructure | 14% | | | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 31% | | | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 2% | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 14% | | | | | | | | | | | | | | | | | | | |
| Refractories | 0.2% | | | | | | | | | | | | | | | | | | | |
| Transport | 18% | | | | | | | | | | | | | | | | | | | |
| Production yield | 75% (Helbig et al., 2020, based on Johnson et al., 2006) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 73% (Helbig et al., 2020, based on Johnson et al., 2006). | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | |
| New scrap recovery | <p>A new scrap recovery of 44% can be calculated based on the global chromium MFA of 2000 (Helbig et al., 2020, based on Johnson et al., 2006). This yield is lower than that of other steel alloying elements, as downgraded new scraps were accounted for as fabrication losses in the MFA of Johnson et al. (2006).</p> <p>Recycling losses of new scraps were here re-allocated to remelting, and a new scrap recovery of 68% was calculated. In comparison to the new scrap recovery previously reported, this new scrap recovery yield is closer to that of nickel (84%; cf. Table B23). Nickel is used in stainless steels in</p> | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | |

| | | |
|-------------------------------|---|---|
| | similar proportions as chromium. This difference may partly be explained by the lower value of ferritic stainless steel in comparison to nickel-containing austenitic stainless steel, and because the former are harder to separate from mixed steel scrap flows than the latter (cf. collection and sorting box). | |
| Remelting | A remelting yield of 54% can be calculated based on the global chromium MFA of 2000 (Helbig et al., 2020, based on Johnson et al., 2006). However, the current global EOL-RR of chromium suggest a much higher remelting yield. It was thus recalculated using our end-use distribution with the reported remelting yields of stainless steel uses per sector of Reck et al. (2010), resulting in an average remelting yield of chromium of approximately 90%. We assumed that this remelting yield also applied to new scraps that were recovered. | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | While negligible dissipation in use can be expected from metal applications of chromium, approximately 2.5% of chromium may leach from treated wood products over their lifetimes (Ciacci et al., 2015). The rate is corrected to 0.2% dissipation in use for the construction category when considering the share of chromium used in wood products aggregated in that sector. Moreover, some of the other uses of chromium may be dissipated in use. Ciacci et al. (2015) estimated that about 16% of chromium used in yellow paint is inherently dissipated in road paint. Leather tanning can also be considered to be dissipated in use (BRGM, 2017d). The exact share of chromium used in these applications is uncertain, but it was estimated to represent less than 1% of the global distribution of chromium uses. The resulting dissipation in use for these applications is taken into account in an estimated dissipation in use of 1% applied to the Other industrial, military & energy applications sector. Finally, the use of chromite as foundry sand for mold casting is considered to be totally dissipated in use over a lifetime of 1 year. | Per sector; please refer to Supplementary Data |
| Collection and sorting | The collection and recycling/remelting steps are aggregated in the global MFA of chromium of Johnson et al. (2006) underlying the works of Helbig et al. (2020). An EoL-RR of 54% was calculated based on that MFA. It was also reported by Nuss et al. (2014) using the same MFA reference, which they applied to all of chromium end-use applications. However, the latter also lacks a distinction between collection and remelting yields, and includes unrecyclable applications as part of the global EoL-RR. Hence, additional information is gathered in order to obtain application specific collection rates. Most chromium is thought to be collected as part of steel products (Graedel et al., 2011); between 70 and 80% of stainless steels, accounting for over 70% of chromium end uses, get recycled (BRGM, 2017d). However, non-functional recycling of chromium often occurs when chromium unintentionally enters old steel scrap flows (Nakajima et al., 2013; Ohno et al., 2014). Austenitic steels are easier to separate from old scrap steel flows in comparison to ferritic stainless steel; and the alloying content of ferritic steel is diffused in carbon steel recycling flows | Per sector; please refer to Supplementary Data |

(Nakajima et al., 2013). Reck et al. (2010) estimated that, in 2005, 79% of steel products were collected for recycling, out of which 70% was recycled in stainless steel and 9% was downcycled in carbon steel flows (Reck et al., 2010). We use the estimates of Reck et al. (2010) to calculate the collection and remelting yields of chromium used in various applications made out of stainless steel. Values for other chrome steels and alloys are calculated using the lower range of values reported for stainless steel values as proxies (cf. Remelting box).

Moreover, chromium contained in chemicals and refractory (“chrome-mag”) applications are considered not to be recyclable (Ciacci et al., 2015). We attributed a collection yield of 0% to these applications. The end-use of chemicals reported as CCA preservative is considered in order to adjust the collection rate applied to construction products. The following collection yields are reported, based on Reck et al. (2010): Alloys & solders, 60%; Construction, 82%; Household appliances, 70%; Infrastructure, 92%; Mechanical equipment, 92%; Other industrial, military & energy applications, 60%; Transport, 87%; and others, 0%. The collection rates and remelting yields for chromium in various steel and stainless steel products are quite alike those reported for iron based on steel product collection rates (cf. Table B21) and fit within the 70-80% EOL-RR reported by the BRGM if a constant end-use distribution over time is assumed. They are therefore estimated to be reasonably plausible.

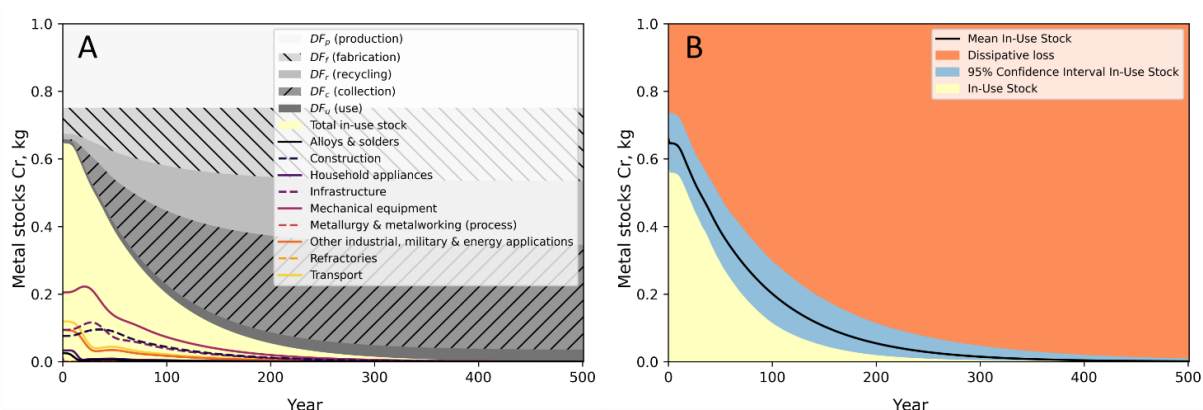


Figure B12. In-use stocks and losses of chromium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.11 Manganese**Table B20. Manganese.**

| Manganese | Mn, element number 25 | Uncertainty |
|------------------|--|--|
| End uses | <p>Manganese is a basic constituent of steel. Around 90% of the global manganese production is consumed by the steel industry, in which it is used to deoxidize and desulfurize iron, and as an alloying agent decreasing steel's brittleness and increasing its strength (6 to 9 kg of manganese is used per ton on steel) (USGS, 2014). Other manganese uses include chemicals (animal feed, pesticides, water treatment), batteries, and non-ferrous alloys (aluminium and copper alloys) (Jones, 1994).</p> <p>Nuss et al (2014) report the global end-uses of manganese in 2008. The European Commission reports global end-use of manganese for the year 2014 (European Commission, 2017b). In 2014, steel and aluminium alloys accounted for 87% and 6% of the global demand of manganese, respectively. Moreover, 5% of the global demand was used in chemicals, and 2% was used in the cathodes of batteries. We disaggregate end-uses of manganese in steel and other alloys based on Europe data for the years 2012-2016 (European Commission, 2020c), average USGS data for the years 2015-2019 (retrieved from USGS Mineral Commodity Statistics for these years), as well as global end-uses of steel reported by the World Steel Association (World Steel Association, 2019, 2020a). Asia uses a large proportion of the total steel products, with China alone consuming nearly half of the world total (World Steel Association, 2019). Similarly, Sun and colleagues (2020) reported that China accounted for 48% of the global apparent consumption of manganese, highlighting the correlation between steel and manganese consumption. Of the 6% reported to be used in non-ferrous alloys, one third is assumed to be used in aluminium cans given the important volume produced (Clarke and Upson, 2017). Chemicals are used in a wide variety of applications, most of which are estimated to be dissipative uses such as animal feed, fertilizers, maneb (fungicide), as well as potassium permanganate used for water purification, waste water treatment and odor control (International Manganese Institute, 2021).</p> <p>Moreover, around 30% of manganese used in steelmaking is used for deoxidization and desulfurization, while the remaining 70% is used in the alloy as part of the final product (USGS, 2014). Therefore, we report that 30% of the manganese used in steelmaking is for deoxidization and desulfurization purposes (about 27% of the total end-use of manganese); and the remainder of the end-uses are normalized to 70% of the end-use applications of steel products.</p> <p>Based on this information, data matching and reconciliation into end-use sectors is performed, providing the following estimates considered to be representative of the global yearly averages circa 2015-2019:</p> | <p>U1: 2 U2: 1 U3: 1 U4: 1 U5: 1</p> |

| | | | | | | | | | | | | | | | | | | | | | | |
|--|---|---|----|--|----|-----------|----|--------------|-----|----------------------|----|----------------------|----|-------------------------------------|-----|-----------------------------------|----|-----------|----|-----------|-----|--|
| | <table><tr><td>Alloys & solders</td><td>4%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>2%</td></tr><tr><td>Chemicals</td><td>5%</td></tr><tr><td>Construction</td><td>32%</td></tr><tr><td>Household appliances</td><td>3%</td></tr><tr><td>Mechanical equipment</td><td>9%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>26%</td></tr><tr><td>Other electrical & metal products</td><td>7%</td></tr><tr><td>Packaging</td><td>2%</td></tr><tr><td>Transport</td><td>11%</td></tr></table> | Alloys & solders | 4% | Batteries (consumer electronics & lead acid) | 2% | Chemicals | 5% | Construction | 32% | Household appliances | 3% | Mechanical equipment | 9% | Metallurgy & metalworking (process) | 26% | Other electrical & metal products | 7% | Packaging | 2% | Transport | 11% | |
| Alloys & solders | 4% | | | | | | | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 2% | | | | | | | | | | | | | | | | | | | | | |
| Chemicals | 5% | | | | | | | | | | | | | | | | | | | | | |
| Construction | 32% | | | | | | | | | | | | | | | | | | | | | |
| Household appliances | 3% | | | | | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 9% | | | | | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 26% | | | | | | | | | | | | | | | | | | | | | |
| Other electrical & metal products | 7% | | | | | | | | | | | | | | | | | | | | | |
| Packaging | 2% | | | | | | | | | | | | | | | | | | | | | |
| Transport | 11% | | | | | | | | | | | | | | | | | | | | | |
| Production yield | <p>A historical study of manganese flows in the US is available (Jones, 1994), along with national MFAs for manganese in the US in 1998 (USGS, 2004b), South Korean steel industry in 2005 (Jeong et al., 2009) and Japanese steel industry, also in 2005 (Nakajima et al., 2008).</p> <p>In 2019, manganese was mostly produced as silicomanganese (1.73 billion mt), followed by manganese ores (20.3 million dry mt) and high carbon ferromanganese (4 million mt) (International Manganese Institute, 2019). To a lesser extent, low and medium carbon ferromanganese are also produced along with electrolytic manganese metal (EMM) and electrolytic manganese dioxide (EMD) (Elliott et al., 2018a; International Manganese Institute, 2019). In 2019, 1.52 million mt of EMM was produced from manganese ores, most of which in China with 97% of global EMM production (International Manganese Institute, 2019).</p> <p>On top of the manganese content in iron ores, manganese is often directly extracted as an alloying agent through the additions of steel scraps, manganese ores and manganese alloys at different stages of the steelmaking process, making it difficult to determine specific yields for the production and fabrication processes separately. EMM is also used for the production of copper and aluminium alloys. Elliott et al. (2018a) provide a detailed review of the major production processes of manganese alloying materials used in steelmaking. The production yield is here estimated to cover the share of manganese that remains in the EMM, EMD, ferromanganese or silicomanganese before these are used in steelmaking or in other alloys and products.</p> <p>Westfall et al. (2015) report a 68.8% recovery rate for the production of ferromanganese from manganese ores. A yield of 65% is calculated from the data in the ES for manganese compounds and metal in the US in 1998 (USGS, 2004b). South Korean data indicate a similar yield of 69% for the production of crude steel (Jeong et al., 2009). Dashevskiy et al. (2013) report 45 to 40% losses of manganese to slags in the production of manganese ferroalloys with the silicothermal process. Elliott et al. (2018b) estimated 40% loss of MnO to the slag phase during carbothermic reduction of manganese oxides from manganese ores in the conventional FeMn process. Elliott et al. (2018a) reported a global</p> | U1: 3 U2: 1 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | | | |

| | | |
|--------------------------------------|--|---|
| | average of 85% recovery from all production routes for alloying materials; however, this yield does not seem to cover the operations occurring prior to the smelting (for manganese alloys) or electrowinning processes (for EMM and EMD production). When considering the yields of ore processing & beneficiation and sinter production of FeMn (Westfall et al., 2015), the production yield falls back to 71%. Based on these references, we consider an average production yield of 70%. While it is attempted to provide the best possible estimate for the production yield of manganese, there may some losses included in the reported yield that are also accounted for in the use of manganese for deoxidization and desulfurization purposes. This may deserve some attention if a dedicated study of manganese flows is performed. | |
| Fabrication and manufacturing | We approximate the steelmaking (and other alloy/chemicals) yields altogether based on the previously cited literature (Jeong et al., 2009; Nakajima et al., 2008; USGS, 2004b) and the 70% yield that is reported for production. For example, the steelmaking efficiency in the US is measured by dividing 65% reported efficiency from manganese extraction to manganese-bearing metal and compounds with 70% production rate, resulting in a yield of 91% for steelmaking (i.e. alloying manganese content of FeMn, SiMn and EMM into steel). In addition to these yields, additional manufacturing and fabrication losses can be expected to be similar to the fabrication yield of steel products. We assume the latter to correspond to the 87% fabrication yield calculated from US data, which closely matches the yield of fabrication for iron products considered in this dataset (i.e. 89%, cf. Table B21). Combining these yields results in an average yield of 73% for the fabrication and manufacturing processes. | U1: 3 U2: 4 U3: 2 U4: 2 U5: 1 |
| New scrap recovery | We consider a new scrap recovery yield of 95% calculated on statistics for the US in 1998 (USGS, 2004b), which is adjusted to include the unrecovered losses of manganese to slags during steelmaking (approximately 8%), resulting in a new scrap recovery yield of 88%. | U1: 3 U2: 4 U3: 2 U4: 2 U5: 1 |
| Remelting | Based on the consulted literature, we estimate a functional remelting yield of 80%, the rest being lost to slags. There may be some discrepancies between what is considered to be functional recycling between references: cf. the Collection and sorting box below. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | Some steel applications may have minor in-use dissipation, such as the abrasion of railways, though these may be considered to be negligible (Ciacci et al., 2015). Moreover, we estimate that 80% of manganese chemicals are dissipated during use based on a qualitative description of its most common applications (International Manganese Institute, 2021). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Manganese uses as chemicals are thought to be unrecyclable, while uses in steel and non-steel alloys as well as batteries could be recycled (Ciacci et al., 2015). The UNEP reported EoL-RR of over 50% for manganese (Graedel et al., 2011) based on USGS (2004a), while the EC mentions actual functional recovery rates of 10% (European Commission, 2020a). US stats for 1998 suggest a recycling rate of 53% for old scraps of aluminium, iron & steel products containing manganese (USGS, 2004a). The rates reported by the USGS seem to represent old scraps entering the recycling flow rather than actual functional recycling, although they | Per sector; please refer to Supplementary Data |

have been considered as functional recycling rates in the Yale's criticality study (Nuss et al., 2014). Such discrepancies may result from the consideration of different definitions of functional recycling, provided that manganese can potentially be considered to be functionally recycled when it is used as a deoxidization and desulfurization of steel even when it ends up in slags. In this dataset, we assume the actual EOL-RR to be halfway between that reported by the US and that by the EC, with a global EOL-RR of 32%. This value is corrected accordingly with the remelting yield of 80%, resulting in an estimated collection rate of 39% for manganese contained in steel-containing applications and other alloys. Finally, a collection rate of 58% is reported for packaging applications based on aluminum's collection yield (cf. Table B14), and an EOL-RR of 0% is considered for batteries and chemicals based on Nuss et al. (2014).

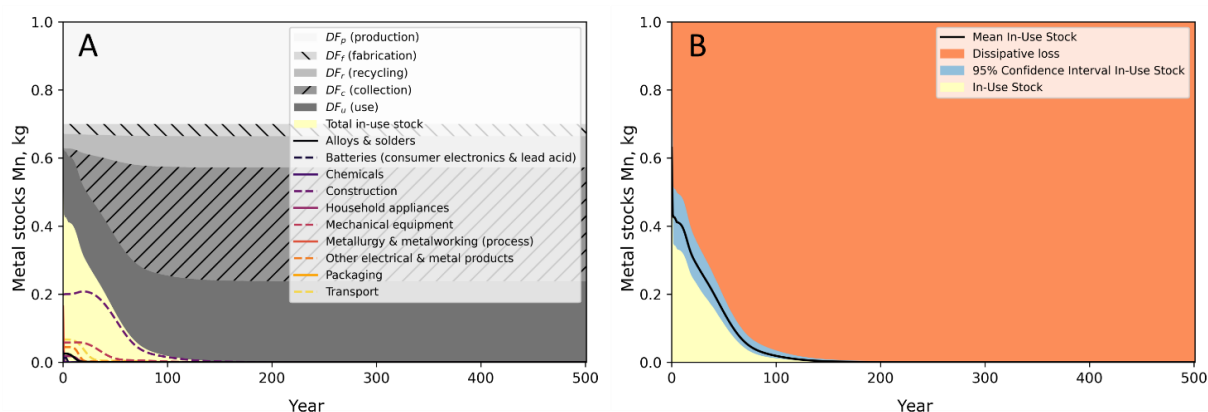


Figure B13. In-use stocks and losses of manganese over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.12 Iron**Table B21. Iron.**

| Iron | Fe, element number 26 | Uncertainty |
|-------------------------------|--|---|
| End-uses | End-uses of iron largely consist of steel applications, which have been used in the Yale studies to establish end-use distributions in 2008 (Graedel et al., 2013). Other end-use distributions of steel are available for the year 2008 (Cullen et al., 2012) and 2019 (World Steel Association, 2020b). The latter end-use distribution is considered to build the current dataset, using the values of 2008 (Cullen et al., 2012) to further disaggregate the construction and metal products categories. The 10% metal products are considered to be split between packaging (0.5%), home appliances (2%) and other metal products (8%). Similarly, the 52% end-use in the construction sector is estimated to be split between construction (31%) and infrastructure (21%). The following end-use distribution is estimated to be representative of 2019: | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| | Construction | 31% |
| | Electronics | 3% |
| | Household appliances | 4% |
| | Infrastructure | 21% |
| | Mechanical equipment | 16% |
| | Other electrical & metal products | 8% |
| | Packaging | 0.5% |
| | Transport | 17% |
| Production yield | 87% (Helbig et al., 2020, based on Wang et al., 2007). Other data for 2004 (Price, 2009) and a more recent global steel MFA for 2008 (Cullen et al., 2012) suggest the 87% yield to be reasonable. Thus, although the MFA is representative of year 2000, we estimate that the production yield remains sensibly the same in recent years given the long history of ironmaking and steelmaking processes. Uncertainty is reported accordingly. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Fabrication and manufacturing | 89% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009): uncertainty is reported accordingly. | U1: 1 U2: 4 U3: 1 U4: 1 U5: 1 |
| New scrap recovery | 100% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009): uncertainty is reported accordingly. | U1: 1 U2: 4 U3: 1 U4: 1 U5: 1 |
| Remelting | 94% (Helbig et al., 2020, based on Wang et al., 2007). Similar values are suggested in other literature (Cullen et al., 2012; Pauliuk et al., 2013; Price, 2009): uncertainty is reported accordingly. | U1: 1 U2: 4 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | Helbig et al. (2020) calculated an average dissipation rate of 1% for all steel products based on Wang et al. (2007). This dissipation in use is seemingly due to atmospheric corrosion of steel used in building and construction as well as friction and corrosion of steel products used in transportation. Ciacci et al. (2015) estimated that about 0.5% of steel is expected to be lost over a lifetime of 50 years in construction (including infrastructure), | Per sector; please refer to Supplementary Data |

| | | |
|-------------------------------|--|---|
| | and 0.4% in the transport sector. These dissipation rates are reported for the corresponding sectors. | |
| Collection and sorting | <p>Helbig et al. (2020) calculated an average collection yield of 74% for all steel products based on Wang et al. (2007). In this dataset, the EoL-RR are disaggregated per sector. The values reported by Nuss et al. (2014), citing Pauliuk et al. (2013), are considered: construction, 87% (attributed to construction and infrastructure), machinery, 82% (attributed to mechanical equipment); transport, 82%; and 58% for other products (attributed to all of the other categories).</p> <p>Considering a remelting yield of 94%, collection rates of 93% are calculated for construction and infrastructure; 87% for transportation and mechanical equipment; and 62% for all other applications. We consider these values to remain representative of recent years, and uncertainty is reported accordingly.</p> | Per sector; please refer to Supplementary Data |

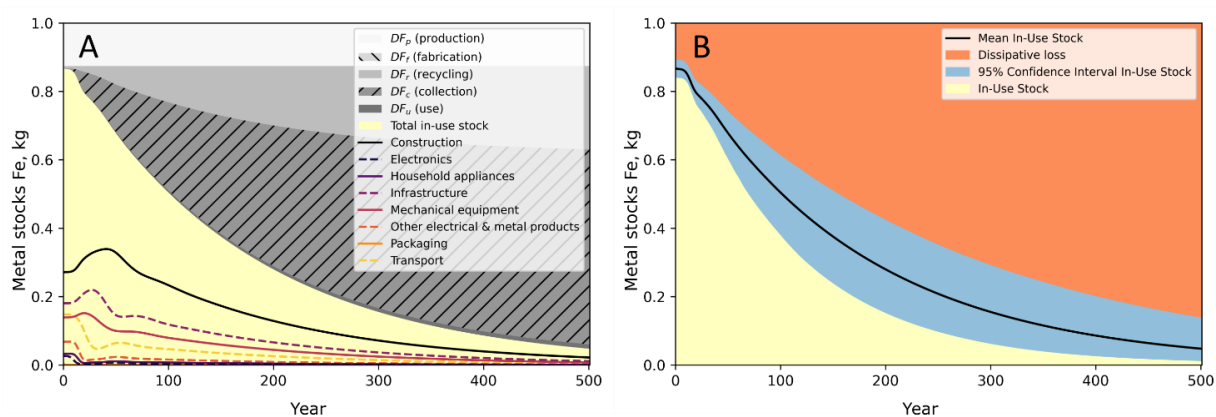


Figure B14. In-use stocks and losses of iron over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.13 Cobalt**Table B22. Cobalt.**

| Cobalt | Co, element number 27 | Uncertainty |
|-----------------|---|--|
| End-uses | <p>Cobalt end-use distributions are available for the year 2006 (Graedel et al., 2015), 2011 (Roberts and Gunn, 2014), 2016 (BRGM, 2017e) and 2017 (Fu et al., 2020). The most important use of cobalt is in rechargeable batteries, with 53% of the consumption of cobalt in 2017 (up from 22% in 2006, and 30% in 2011), followed by superalloys (16%).</p> <p>The reported distribution is representative of the year 2017, based on Fu et al. (2020) and matching data to end-use sectors using other complementary information provided for 2016, for which the distribution is similar (BRGM, 2017e). The share of catalysts is split in 2/3 as petroleum refining catalysts (lifetime of 2 years) and 1/3 as polyester precursor and hydroformylation (oxo-process) catalysts (lifetime of 8 years) based on Ciacci et al. (2015) and Harper et al. (2012). Cobalt compounds used as pneumatic and drying agents are classified as Other miscellaneous uses, along with other undefined applications. Superalloys and hardfacing alloys are aggregated in the alloys sector. Pigments are estimated to be used mostly for ceramics and glazes (BRGM, 2017e) and are aggregated in the glass & ceramics sector. Samarium-cobalt magnets are added to the other industrial sector based on typical applications for these magnets (cf. Table B49).</p> <p>Since batteries represented an important share of end-uses of cobalt, its share across different types of applications was further detailed. Fu et al. (2020) reported that, in 2017, 40% out of 53% of cobalt used in batteries was for consumer electronics, the other two important uses being EVs and advanced battery energy storage systems. Given the importance of Chinese consumption of cobalt especially for the rechargeable battery industry (USGS, 2020), we also analyzed the cobalt use in the battery industry in China in recent years (Chen et al., 2020; Liu et al., 2021). According to the distribution of cobalt consumption in several battery applications in China in 2015 (Chen et al., 2020), approximately 35 kt of cobalt was consumed for batteries in total. These include lithium ion, NiMH and NiCd batteries, which were used for about 83% in consumer electronics products (for this analysis, we included electric bicycles and other special vehicles in this category), 6% for energy storage systems and 11% for electric vehicles (including electric and hybrid cars and buses). Moreover, in 2018, cobalt used in lithium ion batteries was estimated to be shared half and half between consumer electronics and electric vehicles, with approximately 10 kt each (Liu et al., 2021). These values suggest a rapid transition of the use of cobalt towards electric vehicles especially in the past 5 years. It is apparent from the studied literature that cobalt has been increasingly used in lithium ion batteries for electric vehicles, while consumer electronics seem to have benefited from an increase of the efficiency of cobalt use in lithium ion batteries (cf. Roberts and Gunn, 2014), reducing the relative share of</p> | <p>U1: 2 U2: 1 U3: 1 U4: 1 U5: 3</p> |

| | | | | | | | | | | | | | | | | | | | | | | |
|--|---|---|-----|--|-----|------------------------------|-----|----------------------------------|----|---|----|--|----|---------------|----|------------------|----|--|----|---------------------|----|--|
| | <p>cobalt in these batteries. Based on this information, we estimate that globally, in 2017, about 20% of cobalt used in batteries was used in EVs, 75% was used in consumer electronics, and 5% was used in energy storage systems. The latter is reported as industrial batteries. Given the sharp trends that are observed, special attention should be paid to the evolution of cobalt uses in batteries if ever it is attempted to update these data. The following distribution is estimated to be representative of the year 2017:</p> <table><tr><td>Alloys & solders</td><td>20%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>40%</td></tr><tr><td>Batteries (electric vehicle)</td><td>11%</td></tr><tr><td>Batteries (utility & industrial)</td><td>3%</td></tr><tr><td>Catalysts (heterogeneous & stable env.)</td><td>2%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>4%</td></tr><tr><td>Cutting tools</td><td>7%</td></tr><tr><td>Glass & ceramics</td><td>5%</td></tr><tr><td>Other industrial, military & energy applications</td><td>3%</td></tr><tr><td>Other miscellaneous</td><td>6%</td></tr></table> | Alloys & solders | 20% | Batteries (consumer electronics & lead acid) | 40% | Batteries (electric vehicle) | 11% | Batteries (utility & industrial) | 3% | Catalysts (heterogeneous & stable env.) | 2% | Catalysts (homogenous & aggressive env.) | 4% | Cutting tools | 7% | Glass & ceramics | 5% | Other industrial, military & energy applications | 3% | Other miscellaneous | 6% | |
| Alloys & solders | 20% | | | | | | | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 40% | | | | | | | | | | | | | | | | | | | | | |
| Batteries (electric vehicle) | 11% | | | | | | | | | | | | | | | | | | | | | |
| Batteries (utility & industrial) | 3% | | | | | | | | | | | | | | | | | | | | | |
| Catalysts (heterogeneous & stable env.) | 2% | | | | | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 4% | | | | | | | | | | | | | | | | | | | | | |
| Cutting tools | 7% | | | | | | | | | | | | | | | | | | | | | |
| Glass & ceramics | 5% | | | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 3% | | | | | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 6% | | | | | | | | | | | | | | | | | | | | | |
| Production yield | 44% (Helbig et al., 2020, based on Harper et al., 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 94% (Helbig et al., 2020, based on Harper et al., 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| New scrap recovery | 5% (Helbig et al., 2020, based on Harper et al., 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| Remelting | <p>While the MFA of cobalt for 2005 allowed to calculate a remelting yield of 31% (Harper et al., 2012), the value is updated given the new values of EoL-RR considered in this dataset (cf. the collection and sorting box).</p> <p>While multiple recycling industries may recycle different cobalt products (Roberts and Gunn, 2014), we assume an average remelting yield of 95%, and the remainder of losses are here attributed to the collection and sorting step.</p> | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| Dissipation in use | Ciacchi et al. (2015) estimated losses of cobalt of 5% in cemented carbides, as well as 9% in catalysts used in the oxo-process (hydroformylation) and 5% in heterogeneous catalysts. Based on this information, we report 5% dissipation in use for catalysts used in petroleum refining, and an average 7% for long lived catalysts (including catalysts used in the oxo process). Other cobalt applications are not considered to be dissipated during use. | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | | | | | |
| Collection and sorting | Helbig et al. (2020) calculated an average collection yield of 22% in 2005, based on Harper et al., 2012). The EoL-RR has seemingly increased rapidly in the following years due to the rapidly increasing use of cobalt in batteries, reaching an estimated EoL-RR of 68% around 2010 (UNEP, 2011). | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | | | | | |

We consider that chemicals (classified in the Other industrial, military & energy applications), short lived petroleum catalysts, glass products and other miscellaneous uses of cobalt are not collected for recycling (Ciacci et al., 2015; Graedel et al., 2015; Roberts and Gunn, 2014). An estimated EoL-RR of 50% is considered for carbides (cutting tools) based on Graedel et al. (2015), 80% for superalloys and 89% for long lived catalysts (Graedel et al., 2015), 90% for electric vehicle batteries and 10% for magnets (Harper et al., 2012). The same 90% value is assumed to apply to energy storage applications (industrial batteries). Furthermore, while it is particularly difficult to track the recycling of cobalt in consumer electronics batteries (see e.g., Chancerel et al., 2016), an estimated EoL-RR of 35% is reported based on the consulted literature. The reported collection yields are calculated considering a remelting yield of 95%.

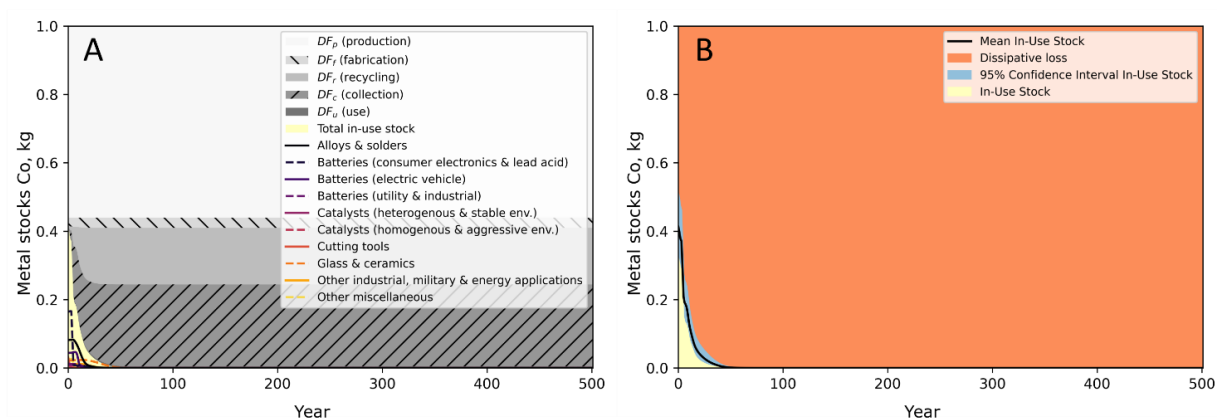


Figure B15. In-use stocks and losses of cobalt over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.14 Nickel**Table B23. Nickel.**

| Nickel | Ni, element number 28 | Uncertainty | | | | | | | | | | | | | | | | | | |
|--|---|-------------------------------------|----|--|----|-----------|----|--------------|-----|-------------|----|----------------------|-----|----------------------|-----|--|----|-----------|-----|---|
| End-uses | <p>Global end-use distributions of nickel are available for several years, e.g. 2008 (Ciacci et al., 2015; Graedel et al., 2015), 2015 (BRGM, 2016b) and for a recent unspecified year (Nickel Institute, 2021a), based on Roskill. The Nickel Institute also provides the distribution of nickel is different materials or semi-products (Nickel Institute, 2021b).</p> <p>The shares of nickel in its end-use applications seem to have remained rather stable over the studied years. Around 65-70% of nickel is used for stainless steel for various applications. Other uses include batteries, other steel alloys and non-ferrous Cu- and Ni- based alloys. The distribution of the Nickel Institute (2021a) is used to establish the end-use distribution of nickel, using the other references to disaggregate some of the reported values. The 10% share reported for electronics is assumed to combine batteries (5% of use of nickel) along with other electronic applications which are disaggregated in two separated categories. Batteries are reported as consumer batteries, considering that electric vehicles and hybrid vehicles mostly replaced NiMH batteries with Li-ion batteries in recent years. The use of nickel in engineering applications is reported as mechanical equipment. Metal goods may include a range of appliances such as dishwashers, washing machines, tools, cutlery, pots and pans (Graedel et al., 2015); these are all classified as household appliances. Finally, nickel compounds used in various applications are also considered as an end-use sector and reported as chemicals, representing 1% of total nickel consumption (Ciacci et al., 2015; Nickel Institute, 2021b). The following end-use distribution is estimated to be representative of years circa 2015-2019:</p> <table><tr><td>Aviation</td><td>3%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>5%</td></tr><tr><td>Chemicals</td><td>1%</td></tr><tr><td>Construction</td><td>16%</td></tr><tr><td>Electronics</td><td>5%</td></tr><tr><td>Household appliances</td><td>22%</td></tr><tr><td>Mechanical equipment</td><td>31%</td></tr><tr><td>Other industrial, military & energy applications</td><td>4%</td></tr><tr><td>Transport</td><td>12%</td></tr></table> | Aviation | 3% | Batteries (consumer electronics & lead acid) | 5% | Chemicals | 1% | Construction | 16% | Electronics | 5% | Household appliances | 22% | Mechanical equipment | 31% | Other industrial, military & energy applications | 4% | Transport | 12% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| Aviation | 3% | | | | | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 5% | | | | | | | | | | | | | | | | | | | |
| Chemicals | 1% | | | | | | | | | | | | | | | | | | | |
| Construction | 16% | | | | | | | | | | | | | | | | | | | |
| Electronics | 5% | | | | | | | | | | | | | | | | | | | |
| Household appliances | 22% | | | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 31% | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 4% | | | | | | | | | | | | | | | | | | | |
| Transport | 12% | | | | | | | | | | | | | | | | | | | |
| Production yield | 79% (Helbig et al., 2020, based on Reck and Rotter, 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 86% (Helbig et al., 2020, based on Reck and Rotter, 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | | | |

| | | |
|-------------------------------|---|---|
| New scrap recovery | 84% (Helbig et al., 2020, based on Reck and Rotter, 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Remelting | 100% (Helbig et al., 2020, based on Reck and Rotter, 2012) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | Dissipation may occur from various chemicals used as e.g. fertilizers, and a dissipation rate of 50% is reported for that sector based on Ciacci et al., (2015). Dissipation in use from other nickel applications is estimated to be negligible (Ciacci et al., 2015), and 0% is reported for all other applications. | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>Helbig et al., (2020) calculated an average collection rate of 63% based on (Reck and Rotter (2012). The BRGM estimates that between 80 and 90% of stainless steels get recycled (BRGM, 2016b). The global EoL-RR of nickel was estimated to be between 57 and 63% by the UNEP's report on recycling rates (UNEP, 2011), and as high as 68% in 2010 by the Nickel Institute (2016). The latter also reported that, out of the 32% that is not functionally recycled, around 17% of nickel contained in EoL products is lost to landfills (mainly metal goods and electrical and electronic equipment), while 15% is non functionally recycled in the carbon steel loop (Nickel Institute, 2021c). Given the calculated remelting yield of 100%, we consider losses to the carbon steel flows as collection losses, unlike in the case on chromium, where the calculated remelting yield is around 90% and includes losses to carbon steel (Table B21). These slight differences between chromium and nickel do not have much influence on the results of the model; however, some attention could be spent on harmonizing these in future research. The following collection rates are reported in this dataset based on Graedel et al. (2015), which are estimated to be representative of the current recycling situation based on the other consulted literature. It is assumed that the collection yield for household appliances is the average collection yield reported for household appliances and metal goods: aviation, 74%; batteries, 29%; chemicals, 0%; construction, 87%; electronics, 29%; household appliances, 39%; mechanical equipment, 87%; and others, 29%.</p> <p>Assuming a constant distribution of nickel between end-use applications over time, these collection rates result in an EoL-RR of 65% across all nickel applications. These data are similar to those underlying the collection and sorting yield of chromium that is also largely used in stainless steel products (Table B19), suggesting some degree of consistency between these two steel-alloying elements.</p> | Per sector; please refer to Supplementary Data |

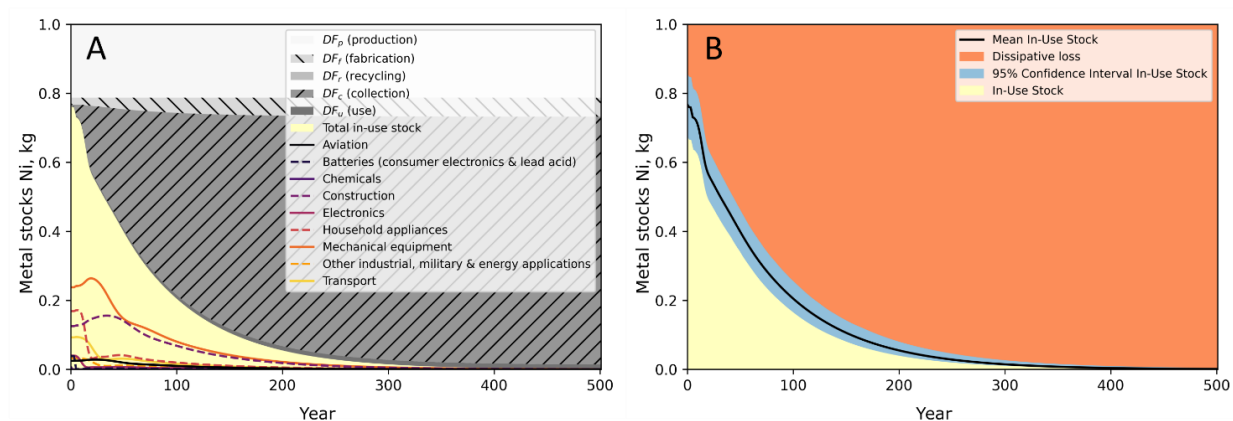


Figure B16. In-use stocks and losses of nickel over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.15 Copper**Table B24. Copper.**

| Copper | Cu, element number 29 | Uncertainty | | | | | | | | | | | | | | | | |
|--|--|---|----|--------------|-----|-------------|-----|----------------|-----|----------------------|-----|--|-----|-------------------|----|-----------|-----|---|
| End-uses | <p>Multiple global end-use distributions are available for copper. Some recent distributions include that of 2016 (BRGM, 2018c) and 2019 (International Copper Study Group, 2020). The latest distribution of 2019 is considered, while the distribution of Ciacci et al. (2015) is used to disaggregate the “equipment” category, representing 31% of end-uses in 2019. Of these, 11% is considered to be used in electronics, 5% in telecommunication, and 14% in a range of other miscellaneous applications. Moreover, 0.5% of end-uses of copper are classified as chemicals, which are thought to be dissipated in use in applications such as fireworks, pesticides and animal feed (Ciacci et al., 2015). Industrial equipment is classified as mechanical equipment. The following distribution is estimated to be representative of the year 2019:</p> <table><tr><td>Chemicals</td><td>1%</td></tr><tr><td>Construction</td><td>28%</td></tr><tr><td>Electronics</td><td>11%</td></tr><tr><td>Infrastructure</td><td>16%</td></tr><tr><td>Mechanical equipment</td><td>12%</td></tr><tr><td>Other industrial, military & energy applications</td><td>14%</td></tr><tr><td>Telecommunication</td><td>5%</td></tr><tr><td>Transport</td><td>13%</td></tr></table> | Chemicals | 1% | Construction | 28% | Electronics | 11% | Infrastructure | 16% | Mechanical equipment | 12% | Other industrial, military & energy applications | 14% | Telecommunication | 5% | Transport | 13% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| Chemicals | 1% | | | | | | | | | | | | | | | | | |
| Construction | 28% | | | | | | | | | | | | | | | | | |
| Electronics | 11% | | | | | | | | | | | | | | | | | |
| Infrastructure | 16% | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 12% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 14% | | | | | | | | | | | | | | | | | |
| Telecommunication | 5% | | | | | | | | | | | | | | | | | |
| Transport | 13% | | | | | | | | | | | | | | | | | |
| Production yield | 83% (Helbig et al., 2020, based on Glöser-Chahoud, 2017). The works of Glöser-Chahoud were published in a scientific article (Glöser et al., 2013), and we considered this value to be as relevant for the uncertainty assessment. | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 82% (Helbig et al., 2020, based on Glöser-Chahoud, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| New scrap recovery | 92% (Helbig et al., 2020, based on Glöser-Chahoud, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Remelting | 100% (Helbig et al., 2020, based on Glöser-Chahoud, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Dissipation in use | Some uses of copper imply dissipation in use. Ciacci et al. (2015) report that about 0.4% of copper used in transport, 0.6% of copper used in plumbing, and 0.7% of copper used in architectural applications may be dissipated during use. The latter two are weighted to represent their share of the construction sector (approximately 2% for architectural uses, and 6% for pipes, out of 28% of copper used in construction). This results in approximately 0.2% of the copper used in construction to be dissipated in use over its lifetime. Furthermore, chemicals are considered to be used in dissipative applications and are attributed a dissipation in use rate of 100%. | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | |

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| Collection and sorting | <p>All of the losses of copper during EOL waste management are attributed to collection, considering the remelting yield of 100%. Helbig et al. (2020) calculated an average collection yield of 47% based on Glöser-Chahoud (2017). In contrast, a slightly lower overall EoL-RR of 40% (International Copper Study Group, 2020) is used as a guideline to establish collection rates per sector. The estimates of Glöser et al. (2013, table 1) are used as a starting point to estimate the following collection yields: construction & infrastructure, 55%; electronics & telecommunication, 25%; mechanical equipment; 40%; transport, 40%; and other uses, 30%. As a general indication, these yields follow similar trends to alloying elements for stainless steel used in similar end-use sectors (nickel and chromium), albeit being lower for copper across its applications.</p> | <p>Per sector; please refer to Supplementary Data</p> |
|-------------------------------|--|---|

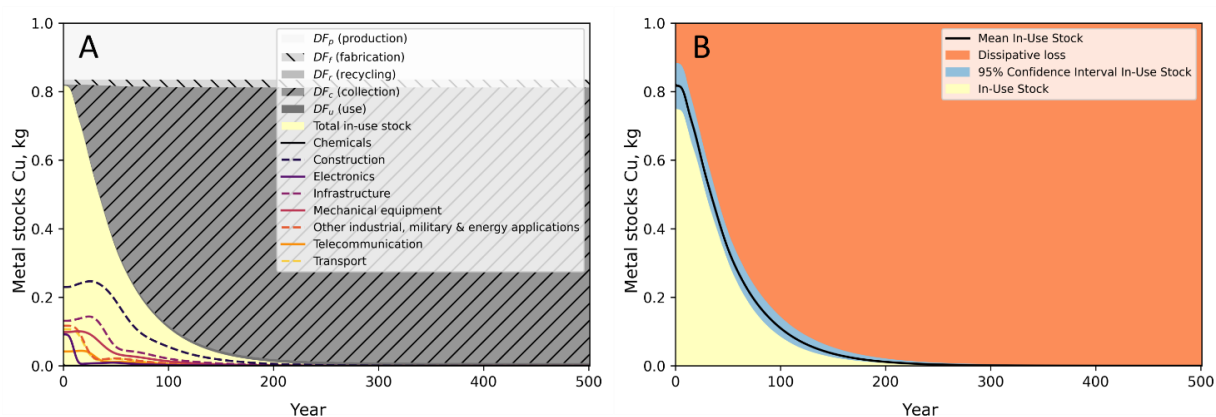


Figure B17. In-use stocks and losses of copper over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.16 Zinc**Table B25. Zinc.**

| Zinc | Zn, element number 30 | Uncertainty | | | | | | | | | | | | | | | | | | |
|---|---|---|----|--------------|-----|-------------|-----|----------------------|----|-----------------------------------|-----|---------------------|----|---------------------|-----|--------|----|-----------|-----|---|
| End-uses | <p>Global end-use distribution of zinc are available for the years 2008 (Harper et al., 2015), 2010 (Meylan and Reck, 2017), 2011 (Ciacci et al., 2015) and 2018 (International Lead and Zinc Study Group, 2021a). The end-uses seem to have remained mostly the same over the 2008-2018 period. Hence, the distribution of Meylan and Reck (2017) is selected to establish the current end-use distribution, because it links first uses of zinc to actual end-use sectors.</p> <p>The most important first use of zinc is for galvanizing steel and iron products (52%), followed by zinc alloying (25%), chemicals (10%), brass (9%) and others (4%) (Meylan and Reck, 2017). Galvanized steel, brass and alloys may each be used for construction, transport, electrical and electronic and miscellaneous applications (Ciacci et al., 2015; Meylan and Reck, 2017). The authors have attributed these first uses to end-use applications. However, it is not possible to replicate the allocation procedure with the data provided by the authors, and some estimations are necessary to establish the end-use distribution for this dataset. It is estimated that about 5% out of the 25% reported in transport applications is for the vulcanization of rubber and improvement of performance of tires, based on Ciacci et al. (2015) as well as the dissipation share attributed to transport in the MFA of Meylan and Reck (2017). Moreover, 20% of miscellaneous uses are reported as other miscellaneous applications, and 80% as protective coatings. Finally, half of the end-uses reported as electrical and electronic products are reported as electronics, and the other half as Other metal and electronic products, to reflect the variety of potential applications. The following distribution is estimated to be representative of 2010, and to be fairly representative of years 2008-2018 given the apparent stability of zinc end-uses over time:</p> <table><tr><td>Agricultural & environmental applications</td><td>1%</td></tr><tr><td>Construction</td><td>33%</td></tr><tr><td>Electronics</td><td>10%</td></tr><tr><td>Mechanical equipment</td><td>7%</td></tr><tr><td>Other electrical & metal products</td><td>10%</td></tr><tr><td>Other miscellaneous</td><td>3%</td></tr><tr><td>Protective coatings</td><td>12%</td></tr><tr><td>Rubber</td><td>5%</td></tr><tr><td>Transport</td><td>20%</td></tr></table> <p>This distribution could benefit from more precise data than those available in the consulted literate to establish the distribution of end-uses of zinc between electronics, home appliances, electrical products and other miscellaneous applications. Nonetheless, most of these applications of zinc are estimated to have lifetimes between 10 and 15</p> | Agricultural & environmental applications | 1% | Construction | 33% | Electronics | 10% | Mechanical equipment | 7% | Other electrical & metal products | 10% | Other miscellaneous | 3% | Protective coatings | 12% | Rubber | 5% | Transport | 20% | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 |
| Agricultural & environmental applications | 1% | | | | | | | | | | | | | | | | | | | |
| Construction | 33% | | | | | | | | | | | | | | | | | | | |
| Electronics | 10% | | | | | | | | | | | | | | | | | | | |
| Mechanical equipment | 7% | | | | | | | | | | | | | | | | | | | |
| Other electrical & metal products | 10% | | | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 3% | | | | | | | | | | | | | | | | | | | |
| Protective coatings | 12% | | | | | | | | | | | | | | | | | | | |
| Rubber | 5% | | | | | | | | | | | | | | | | | | | |
| Transport | 20% | | | | | | | | | | | | | | | | | | | |

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| | years according to (Meylan and Reck, 2017), similarly to the lifetimes reported in this dataset. Therefore, the uncertainty of this end-use distribution is expected to have a small influence on the results of the model for zinc. | |
| Production yield | 84% (Helbig et al., 2020, based on Meylan and Reck, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Fabrication and manufacturing | 78% (Helbig et al., 2020, based on Meylan and Reck, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| New scrap recovery | 91% (Helbig et al., 2020, based on Meylan and Reck, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Remelting | 64% (Helbig et al., 2020, based on Meylan and Reck, 2017) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | About 0.4% of zinc coatings used in construction is dissipated yearly, resulting in 20% zinc being dissipated over a building's lifetime of 50 years (Ciacci et al., 2015). Moreover, the dissipation in use rates are estimated for other applications based on Ciacci et al. (2015) and Meylan and Reck (2017): 100% for agricultural applications; 5% for the protective coatings category (including some uses for industrial and metal working machinery); 5% for other miscellaneous applications (taking into account losses from e.g. sacrificial anodes, paint and lubricants); and 40% for rubber (tires). The dissipation from other applications is estimated to be negligible. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Helbig et al. (2020) calculated an average collection yield of 65% based on Meylan and Reck (2017). The latter reference is used to report collection rates per application category, that are recalculated taking into account the different aggregation into end-use sectors that is used in this dataset. For instance, the collection yield for transport category is corrected to take into account the share of tires included in that category in the works of Meylan and Reck (2017). The following collection rates are calculated: construction, 52%; electronics, 40%; mechanical equipment, 82%; other electrical & metal products, other miscellaneous and protective coatings, 29%; and transport, 61%. Some estimations and end-use aggregations different than that of Helbig et al. (2020) and Meylan and Reck (2017) are made in this dataset. The reported collection yields, combined with the remelting yield of 64%, suggest a global EoL-RR of approximately 30% for zinc if a constant end-use distribution is assumed, similar to that of 33% that was calculated by Meylan and Reck (2017) for 2010. | Per sector; please refer to Supplementary Data |

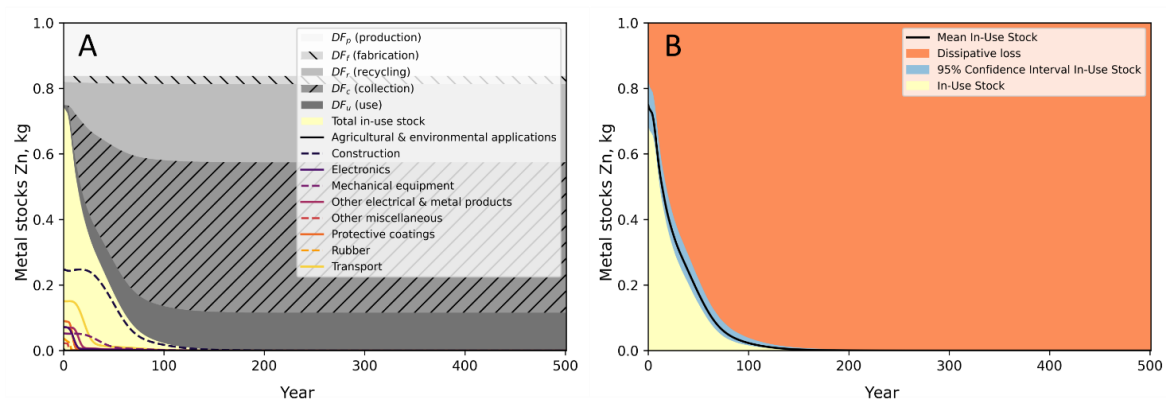


Figure B18. In-use stocks and losses of zinc over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.17 Gallium**Table B26. Gallium.**

| Gallium | Ga, element number 31 | Uncertainty | | | | | | | | | | | | | | | | |
|--|--|-------------------------------------|----|--|----|-------------|-----|----------|-----|-----------------|----|--|----|-------------|----|-------------------|-----|---|
| End-uses | <p>Global end-use distributions are available for 2010 (Butcher and Brown, 2014 and Peiró et al., 2013), 2011 (Licht et al., 2015) and 2013 (BRGM, 2016c). The USGS also provide qualitative and quantitative indications of the major global markets for gallium (GaAs wafers used in e.g. smartphones, GaN used in opto and power semi-conductors, LEDs and radiofrequency devices, and copper-indium-gallium-selenide solar cells) in the Mineral Yearbooks (Jaskula, 2020) and Mineral Commodity Summaries (USGS, 2020). For this dataset, the most disaggregated distribution of Butcher and Brown (2014), also considered in the works of Ciacci et al. (2015), is used as a starting point, and is updated based on other available information (BRGM, 2016c; Jaskula, 2020; Licht et al., 2015; USGS, 2020).</p> <p>Given the variety of uses of semi-conductors and integrated circuits, we estimate that about 70% of gallium is used in various electronics applications, regrouping LEDs used in e.g. computer screens and tablets, as well as integrated circuit boards used for e.g. smartphones, and radiofrequency devices. It is also estimated that 10% of gallium is used in used in various telecommunication and defense applications such as military radars, wireless telecommunication infrastructure and cable television transmission, which are all aggregated in telecommunications. The following distribution is estimated to be representative of years circa 2013-2019:</p> <table><tr><td>Alloys & solders</td><td>5%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>1%</td></tr><tr><td>Electronics</td><td>60%</td></tr><tr><td>Lighting</td><td>10%</td></tr><tr><td>Magnets (small)</td><td>4%</td></tr><tr><td>Other industrial, military & energy applications</td><td>5%</td></tr><tr><td>Solar cells</td><td>5%</td></tr><tr><td>Telecommunication</td><td>10%</td></tr></table> | Alloys & solders | 5% | Catalysts (homogenous & aggressive env.) | 1% | Electronics | 60% | Lighting | 10% | Magnets (small) | 4% | Other industrial, military & energy applications | 5% | Solar cells | 5% | Telecommunication | 10% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 2 |
| Alloys & solders | 5% | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 1% | | | | | | | | | | | | | | | | | |
| Electronics | 60% | | | | | | | | | | | | | | | | | |
| Lighting | 10% | | | | | | | | | | | | | | | | | |
| Magnets (small) | 4% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 5% | | | | | | | | | | | | | | | | | |
| Solar cells | 5% | | | | | | | | | | | | | | | | | |
| Telecommunication | 10% | | | | | | | | | | | | | | | | | |
| Production yield | 2% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 28% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | | | |
| New scrap recovery | 80% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | | | |
| Remelting | 71% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | | | |
| Dissipation in use | Out of all gallium end uses, only is the use as a catalyst thought to be inherently dissipative (Ciacci et al., 2015; Licht et al., 2015). While no actual | Per sector; please refer to | | | | | | | | | | | | | | | | |

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| | amount of gallium is reported to be lost during the use phase of catalysts, these are here reported to be totally dissipated over a lifetime of 2 years. | Supplementary Data |
| Collection and sorting | 0% (Helbig et al., 2020, based on Licht et al., 2015). While small quantities of gallium may be recovered, the EOL recycling of gallium is thought to still be globally negligible today (BRGM, 2016c; Ciacci et al., 2015; European Commission, 2020a). | Per sector; please refer to Supplementary Data |

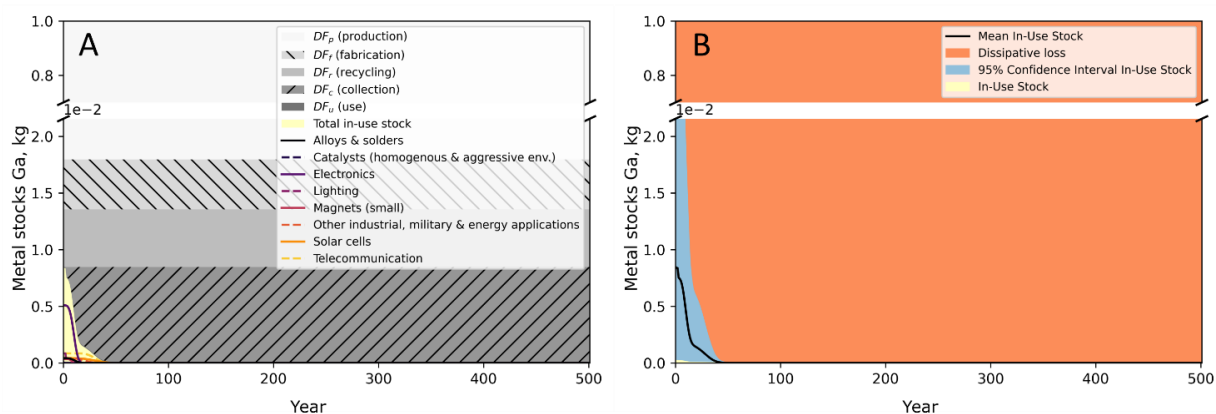


Figure B19. In-use stocks and losses of gallium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.18 Germanium**Table B27. Germanium.**

| Germanium | Ge, element number 32 | Uncertainty |
|-------------------------------|---|---|
| End-uses | End-use distributions of germanium are reported for 2008 (Harper et al., 2015), 2010 (Peiró et al., 2013), 2011 (Licht et al., 2015), 2013 (BRGM, 2015a), and 2015 (Guberman, 2016). End-uses remain fairly constant over the studied years, with similar shares of germanium being used in fiber optic cables, infrared optic devices and polyethylene terephthalate (PET) catalysts (25-35% each). One study estimated a higher share of germanium used in PET catalysts, with around 40% of its total use (Licht et al., 2015). Infrared applications are mostly used in military applications (Guberman, 2016). Other uses include solar cells, semi-conductors used in electronic appliances and phosphors used in lighting applications. | U1: 2 U2: 2 U3: 1 U4: 2 U5: 2 |
| | We consider the most recent distribution of 2015 (Guberman, 2016). The values for the electronics and solar cells applications are disaggregated using the data of (Peiró et al., 2013). Similarly, the ‘other’ category is further refined into lighting applications and other industrial categories. Infrared optics are aggregated within the Other industrial, military & energy applications. Finally, electronics and fiber optic appliances are both aggregated in the electronics category, and PET catalysts are classified in the packaging sector as they typically remain in the bottle, contributing to its brightness and transparency (Ciacci et al., 2015). The following end-use distribution is estimated to be representative of the year 2015: | |
| | Electronics | 39% |
| | Lighting | 9% |
| | Other industrial, military & energy applications | 26% |
| | Packaging | 20% |
| | Solar cells | 6% |
| Production yield | 1% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| Fabrication and manufacturing | 42% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| New scrap recovery | 100% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| Remelting | 51% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| Dissipation in use | Helbig et al. (2020) reported that 52% of germanium is dissipated in use, based on Licht et al. (2015). In the latter study, most dissipative losses result from the use of germanium as a catalyst used to produce PET for bottles. As discussed above, the share of germanium in this application is quite higher than in other end-use distributions reported in the literature. Instead, it is | Per sector; please refer to Supplementary Data |

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| | <p>here considered that 100% of germanium ending up in PET bottles is non-functionally recycled (type C dissipation).</p> <p>While some minor uses of germanium may be dissipative, such as chemotherapy, these were assumed to be a negligible share of total germanium consumption. Other uses can also be assumed to undergo negligible amounts of dissipation during the use phase (Ciacci et al., 2015).</p> | |
| Collection and sorting | <p>Helbig et al. (2020) reported 0% recycling of end-of-life products, based on Licht et al. (2015). While about 12% of EoL germanium is reported to be functionally recycled in Europe, it is mentioned that only a small share of germanium may be collected for recycling from IR optics, while it is unrecoverable from other applications (European Commission, 2020a). This coincides with the EoL-RR estimate of 7.5% for infrared optics reported by Harper et al. (2015). An EoL-RR of 0% is considered for other applications (European Commission, 2020a; Harper et al., 2015).</p> <p>In order to implement this value for IR optics, we extrapolated a collection rate of about 15% for old scraps of IR product (considering the remelting yield of 51%), and adjusted the resulting yield to represent the share of IR optics aggregated in Other industrial, military & energy applications (77%). The resulting collection yield is of 11% for that sector. A collection yield of 0% is reported for other applications.</p> | Per sector; please refer to Supplementary Data |

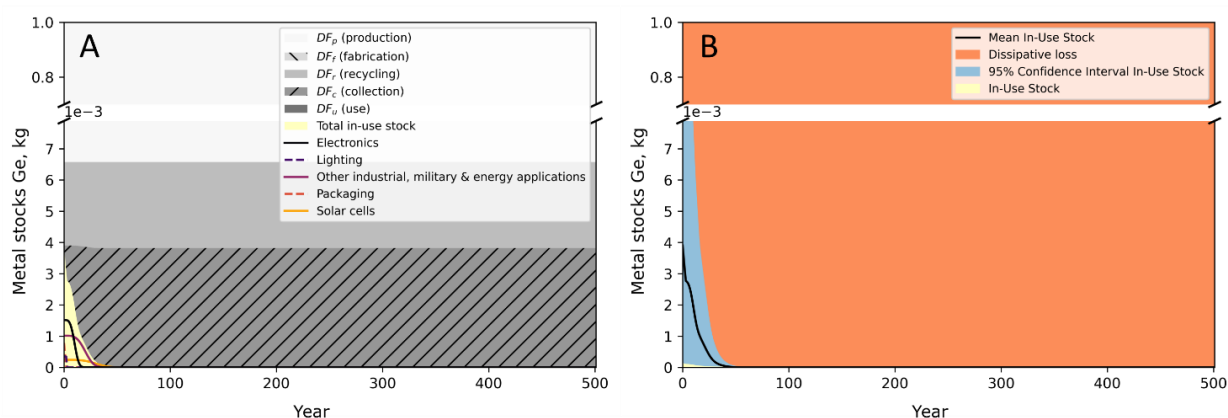


Figure B20. In-use stocks and losses of germanium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.19 Arsenic**Table B28. Arsenic.**

| Arsenic | As, element number 33 | Uncertainty | | | | | | |
|---|--|---|----|------------------|----|------------------------------|-----|---|
| End uses | <p>Common uses of arsenic include CCA treatment for wood products, herbicides and insecticides, grids of lead-acid batteries, gallium-arsenide semiconductor and specialty glass products including optical products (European Commission, 2020c; Shi et al., 2017; USGS, 2020). In Europe, the main use of diarsenic trioxide is to remove impurities from zinc during the electro-winning process for zinc production (European Commission, 2020c).</p> <p>A global end-use distribution for arsenic is reported for the year 2008, however it is based on estimates for the US (Ciacci et al., 2015; Nassar et al., 2012). In addition, end-uses in Europe are reported for years around 2009-2010 (European Commission, 2020c). SFAs of antimony for mainland China in 1990, 2000 and 2010 (Shi et al., 2017), as well as for Taiwan in 2008 (Chen et al., 2013), provide additional information on end-uses of arsenic.</p> <p>For this dataset, we construct an approximate global end-use distribution based on the available data for these four regions or countries circa 2008-2010. Considering production data for 2008-2010 reported by the USGS, as well as consumption data in the literature cited above, we estimate that the consumption of arsenic by China, US, Europe and Taiwan represented about 60%, 10%, 3% and 0.3% of global consumption during these years, respectively, covering approximately 75% of the total consumption. The consumption of arsenic reported as zinc alloys in China is assumed to be in a metallurgical process similar to that in Europe. Chemicals use in Europe (total 7%) is assumed to be split between wood treatment (94%), agricultural products (5%) and electronics (1%). Wood and pesticide category for the US is assumed to split between wood products (95%) and agricultural products (5%) based on historical US end-use statistics (USGS, 2017). Other uses reported in the US are assumed to be split evenly between glass, lead alloys (e.g., for ammunition) and lead batteries.</p> <p>Moreover, we assume that half of arsenic used for alloys is added to lead alloys for shot and bullet production (Ciacci et al., 2015); these are accounted for in the Other punctual applications. Finally, wood products are categorized in infrastructure, and copper and lead alloys in alloys. Semi-conductors are aggregated in electronics, which also includes photovoltaic panels. Fertilizers, pesticides and herbicides are categorized in agricultural & environmental applications. The following distribution is estimated to represent the global end-uses of arsenic circa 2008-2010:</p> <table><tr><td>Agricultural & environmental applications</td><td>2%</td></tr><tr><td>Alloys & solders</td><td>2%</td></tr><tr><td>Batteries (electric vehicle)</td><td>29%</td></tr></table> | Agricultural & environmental applications | 2% | Alloys & solders | 2% | Batteries (electric vehicle) | 29% | U1: 2 U2: 3 U3: 2 U4: 3 U5: 2 |
| Agricultural & environmental applications | 2% | | | | | | | |
| Alloys & solders | 2% | | | | | | | |
| Batteries (electric vehicle) | 29% | | | | | | | |

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|--------------------------------------|--|---|----|------------------|-----|----------------|-----|-------------------------------------|----|-----------------------------|----|--|
| | <table><tr><td>Electronics</td><td>4%</td></tr><tr><td>Glass & ceramics</td><td>28%</td></tr><tr><td>Infrastructure</td><td>27%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>5%</td></tr><tr><td>Other punctual applications</td><td>2%</td></tr></table> | Electronics | 4% | Glass & ceramics | 28% | Infrastructure | 27% | Metallurgy & metalworking (process) | 5% | Other punctual applications | 2% | |
| Electronics | 4% | | | | | | | | | | | |
| Glass & ceramics | 28% | | | | | | | | | | | |
| Infrastructure | 27% | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 5% | | | | | | | | | | | |
| Other punctual applications | 2% | | | | | | | | | | | |
| Production yield | <p>The process yields for arsenic are calculated based on Chinese SFA in 2010 (Shi et al., 2017). This is estimated to provide a reasonable depiction of global yields, since China produces and transforms more arsenic than any other country. The values were compared with the SFA of arsenic in Taiwan (Chen et al., 2013) to ensure some degree of consistency.</p> <p>Taking into account arsenic contents of arsenic, lead, zinc, copper and tin ores, the calculated production yield is of 8%. Similarly, most arsenic extracted and processed in Taiwan is not used in products for its specific functionalities, as most extracted arsenic ends up in various aggregates used in construction (Chen et al., 2013).</p> | U1: 1 U2: 3 U3: 2 U4: 2 U5: 2 | | | | | | | | | | |
| Fabrication and manufacturing | 98% is reported in this dataset, based on Shi et al. (2017). The yield is close to 100% in Taiwan (Chen et al., 2013). | U1: 1 U2: 3 U3: 2 U4: 2 U5: 2 | | | | | | | | | | |
| New scrap recovery | The recycling of arsenic from new scraps may occur in the manufacture of GaAs semiconductors (Ciacci et al., 2015). However, given that no new scrap recovery was noted in the SFA of arsenic, it is assumed that the reported manufacturing yield of 98% includes new scrap recovery and remelting when it occurs, and 0% is reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | |
| Remelting | 0% (cf. new scrap recovery, and 0% EOL-RR is considered) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | |
| Dissipation in use | <p>100% of agricultural products and of metallurgical use (desulfurization) of arsenic are estimated to be used dissipatively (Ciacci et al., 2015). The authors mentions that some dissipation may result from the use of arsenic in CCA preservatives, although no percentage is explicitly reported in the study. We assume a dissipation in use rate of 5% due to the lixiviation of treated wood products.</p> <p>While other minor end-uses of arsenic may be dissipative, such as the use in cancer treatment and fireworks (Ciacci et al., 2015), these are not considered in the end-use distribution and thus are not reported in this dataset. Other applications are not considered to be dissipated during use.</p> | Per sector; please refer to Supplementary Data | | | | | | | | | | |
| Collection and sorting | Arsenic is unrecyclable in most of its applications, and is not targeted for recycling currently (Ciacci et al., 2015; Graedel et al., 2011; USGS, 2020). | Per sector; please refer to Supplementary Data | | | | | | | | | | |

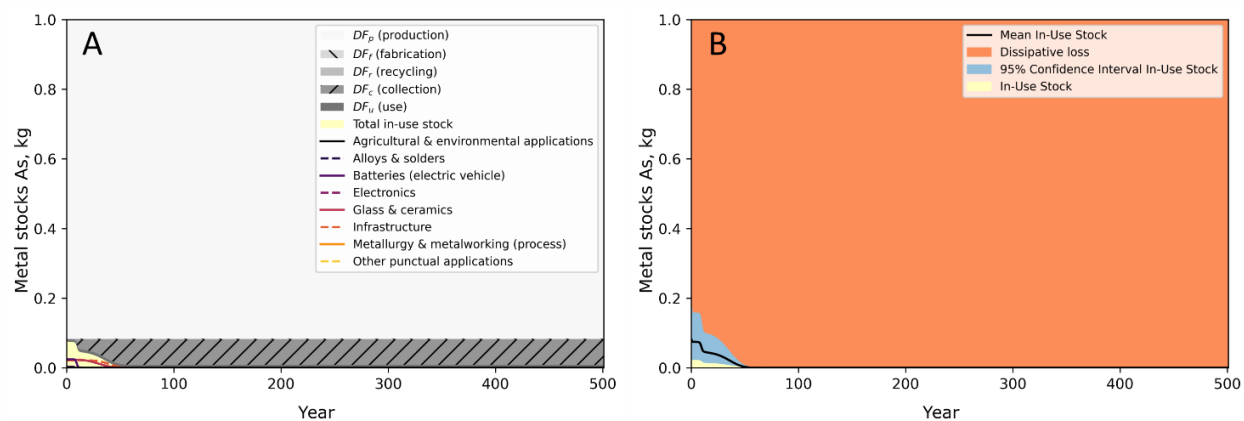


Figure B21. In-use stocks and losses of arsenic over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.20 Selenium**Table B29. Selenium.**

| Selenium | Se, element number 34 | Uncertainty | | | | | | | | | | | | | | | | | | | | |
|--|--|---|-----|------------------|-----|-----------|----|-------------|----|------------------|-----|-------------------------------------|-----|--|----|---------------------|----|-----------------------------|----|-------------|----|---|
| End-uses | <p>The USGS reported global estimates of selenium consumption in its Mineral Commodity Summaries for several past years. The end-use distribution for the year 2019 (USGS, 2020) is used to build this dataset. It is slightly refined with additional information provided by Kavlak and Graedel (2013b) and Ciacci et al. (2015). The electronics sector is divided between solar cells and photoreceptors, used in e.g. photocopy machines, using a 4:6 ratio (cf. data for 2010, provided by Kavlak and Graedel, 2013b, table A.3 of the Supporting information). Photoreceptors are aggregated in the electronics category, while solar cells are reported in their dedicated sector.</p> <p>The most important uses of selenium are in glassmaking and metallurgical processes. Kavlak and Graedel (2013b) considered these two uses to be dissipative. Yet, selenium in fact mostly remain in the manufactured products, possibly contributing to its functions, and could in theory be recycled (Ciacci et al., 2015). As noted in section B.1.4, we consider such uses as dissipation of type C. Moreover, about 20% of the selenium used in glassmaking is here considered to be a punctual use of selenium to reflect dissipation is use losses, while the remaining 80% is considered to be part of the glass product (Ciacci et al., 2015) and is reported as such. Regarding metallurgical processes, selenium is either used as an alloying element for steel, copper, lead alloys, or added to the electrolytic manganese production process to increase its efficiency (Kavlak and Graedel, 2013b). We estimate that 10% out of its 40% share reported in metallurgy are dissipative process uses of selenium where it may volatilize or is lost to slags; and the remaining share of 30% is reported in the alloys category.</p> <p>Finally, due to the range of applications for selenium chemicals (catalysts, pigments for paint and plastics, heat stabilizing agent for rubber production), half were reported as chemicals, and the other half as other miscellaneous applications to reflect the variability of lifetime across their different potential applications. The following distribution is estimated to be representative of the global end-uses of selenium in 2019:</p> <table><tr><td>Agricultural & environmental applications</td><td>10%</td></tr><tr><td>Alloys & solders</td><td>30%</td></tr><tr><td>Chemicals</td><td>5%</td></tr><tr><td>Electronics</td><td>4%</td></tr><tr><td>Glass & ceramics</td><td>20%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>10%</td></tr><tr><td>Other industrial, military & energy applications</td><td>5%</td></tr><tr><td>Other miscellaneous</td><td>5%</td></tr><tr><td>Other punctual applications</td><td>5%</td></tr><tr><td>Solar cells</td><td>6%</td></tr></table> | Agricultural & environmental applications | 10% | Alloys & solders | 30% | Chemicals | 5% | Electronics | 4% | Glass & ceramics | 20% | Metallurgy & metalworking (process) | 10% | Other industrial, military & energy applications | 5% | Other miscellaneous | 5% | Other punctual applications | 5% | Solar cells | 6% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| Agricultural & environmental applications | 10% | | | | | | | | | | | | | | | | | | | | | |
| Alloys & solders | 30% | | | | | | | | | | | | | | | | | | | | | |
| Chemicals | 5% | | | | | | | | | | | | | | | | | | | | | |
| Electronics | 4% | | | | | | | | | | | | | | | | | | | | | |
| Glass & ceramics | 20% | | | | | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 10% | | | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 5% | | | | | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 5% | | | | | | | | | | | | | | | | | | | | | |
| Other punctual applications | 5% | | | | | | | | | | | | | | | | | | | | | |
| Solar cells | 6% | | | | | | | | | | | | | | | | | | | | | |

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| Production yield | 4% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Fabrication and manufacturing | 85% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| New scrap recovery | 24% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Remelting | 100% (Helbig et al., 2020, based on Kavlak and Graedel, 2013b) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | The uses of selenium in glass production (reported as other punctual application) and agricultural applications are considered to be wholly dissipated during use (Ciacci et al., 2015). Moreover, its use reported in the metallurgical processes is considered to be dissipated in use (Ciacci et al., 2015). Selenium used in other applications is not considered to be dissipated in use. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Helbig et al. (2020) calculated an average collection rate of 50% based on Kavlak and Graedel (2013b). However, this yield covered only a few categories summing up to 13% of the total uses, while the remaining 87% of end-uses were considered to be dissipative uses. Moreover, while selenium was historically recovered from rectifiers and photocopiers, it is nowadays seldom used in these applications, and the selenium contained in most of its current applications being put on the market is not readily recyclable (European Commission, 2020c; Kavlak and Graedel, 2013b). The BRGM estimates that the EOL-RR of selenium is below 5% (BRGM, 2018d). Selenium contained in old alloy scraps is not considered to be targeted during waste management and recycling. Based on this information, a conservative collection yield of 10% is reported for electronics, and 0% is reported for all other uses. | Per sector; please refer to Supplementary Data |

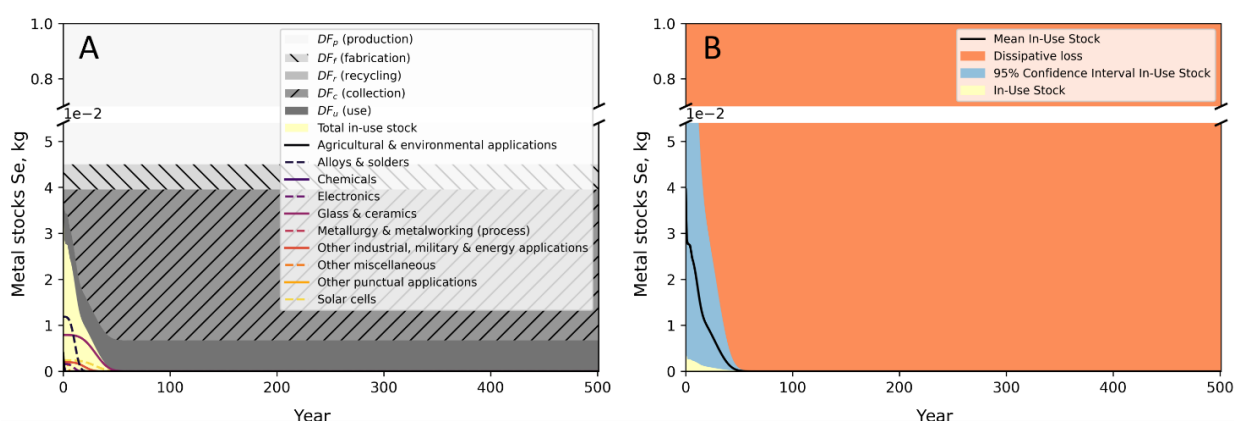


Figure B22. In-use stocks and losses of selenium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.21 Strontium**Table B30. Strontium.**

| Strontium | Sr, element number 38 | Uncertainty | | | | | | | | | | | | | | | | |
|--|--|-------------|----|------------------|----|-----------------|-----|-------------------------------------|----|--|----|-----------------------------|-----|-----------|----|---------------|-----|---|
| End uses | <p>Strontium can be directly used as a drilling fluid for oil and gas production (as part of the celestine mineral), and in a range of applications such as the electrolytic production of zinc, pyrotechnics and signals, magnets, pigments and fillers, master alloys, glass and for cancer treatment (European Commission, 2020a; USGS, 2020). Celestine is isostructural with barytes, that are also used for well drilling (cf. Table B44). USGS statistics report important uses of celestine in drilling fluids since 2006.</p> <p>The Yale criticality studies and the EC report values based on US statistics (European Commission, 2020a; Graedel et al., 2013; Panousi et al., 2016). The 2020 EC criticality study report that no data is available beyond those of the USGS for recent years (European Commission, 2020a), though it is estimated that European uses are more similar to the use of strontium compounds than those of celestine since few oil and gas projects occur in Europe compared to the US.</p> <p>In this dataset, global end-use values are estimated from the US statistics for 2019 (USGS, 2020). In 2019, the US consumed around 7% of the global production of strontium, with 17 000 of the 220 000 tons of strontium produced worldwide. This corresponds to the average of approximately 4-10% consumed annually from years 2015-2019. Since the US produces around 20% of the total oil and natural gas production worldwide, we roughly estimate the actual average global strontium end-use as a drilling fluid to be one half of 64% (32%). The remaining share of strontium uses are corrected to 100% proportionally to their original distribution. Based on qualitative descriptions of major end-uses in (European Commission, 2020a), strontium pigments are assumed to be used mostly in ceramic glazes, and master alloys are assumed to be split half and half between the transport and aviation sectors. Moreover, half of the “other” category is assumed to be used in various glass products. Pyrotechnics and signals are added to Other punctual applications. The final distribution considered in this dataset is estimated to be representative of 2019:</p> <table><tr><td>Aviation</td><td>3%</td></tr><tr><td>Glass & ceramics</td><td>9%</td></tr><tr><td>Magnets (small)</td><td>23%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>6%</td></tr><tr><td>Other industrial, military & energy applications</td><td>3%</td></tr><tr><td>Other punctual applications</td><td>23%</td></tr><tr><td>Transport</td><td>3%</td></tr><tr><td>Well drilling</td><td>32%</td></tr></table> <p>This distribution is very different than that reported by other authors earlier years, which included 55% used in television tubes. Flat screens no longer make use of strontium. Another difference that may explain discrepancies is</p> | Aviation | 3% | Glass & ceramics | 9% | Magnets (small) | 23% | Metallurgy & metalworking (process) | 6% | Other industrial, military & energy applications | 3% | Other punctual applications | 23% | Transport | 3% | Well drilling | 32% | U1: 2 U2: 1 U3: 4 U4: 3 U5: 3 |
| Aviation | 3% | | | | | | | | | | | | | | | | | |
| Glass & ceramics | 9% | | | | | | | | | | | | | | | | | |
| Magnets (small) | 23% | | | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 6% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 3% | | | | | | | | | | | | | | | | | |
| Other punctual applications | 23% | | | | | | | | | | | | | | | | | |
| Transport | 3% | | | | | | | | | | | | | | | | | |
| Well drilling | 32% | | | | | | | | | | | | | | | | | |

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| | that other studies may not have considered celestine used for well drilling as a strontium use, which is here the case. | |
| Production yield | Panousi et al. (2016) reported a yield of 76% based on an informed estimate. Considering that the production of celestine requires less processing than that of pure strontium, we estimate a slightly higher average yield of 80%. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 1 |
| Fabrication and manufacturing | Assumption of a yield of 90%. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | 0% (assumed to be accounted for in fabrication and manufacturing losses) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | Assumed to be accounted for in fabrication and manufacturing losses, and a collection yield of 0% is reported for all applications (no EoL recycling is considered to occur). | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | Uses of strontium for well-drilling, zinc production and pyrotechnics & signals (included in other punctual applications) are considered to be dissipative. Other uses are not expected to be dissipated in use given the nature of the applications. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Local recycling of drilling fluids may occur (cf. barium, Table B44); we consider that these are included in the reported lifetime of 1 year. Negligible (<1%) recycling rates are reported for all other strontium uses (European Commission, 2020a; Panousi et al., 2016). We consider an EoL-RR of 0% for all strontium uses in this dataset. | Per sector; please refer to Supplementary Data |

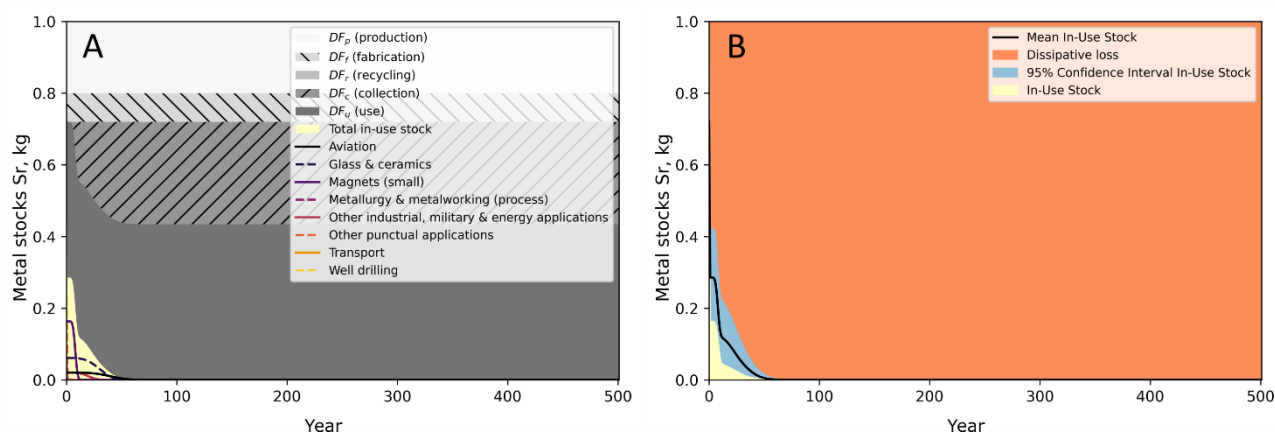


Figure B23. In-use stocks and losses of strontium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.22 Yttrium**Table B31. Yttrium.**

| Yttrium | Y, element number 39 | Uncertainty | |
|-------------------------------|--|---|------|
| End uses | End-uses reported in the 2014 European criticality report (European Commission, 2014) were matched and disaggregated with end-use data from Peiró et al. (2013). The general methodology for REEs is described in section B.2.3.3.2. The following distribution is estimated to be representative of the global end-uses of yttrium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 3 | |
| | Electronics | | 10% |
| | Glass & ceramics | | 21% |
| | Lighting | | 69% |
| | Other industrial, military & energy applications | | 0.4% |
| Production yield | 66% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 | |
| Fabrication and manufacturing | 85% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 | |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 | |
| Remelting | 100% (assumption) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data | |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 10% is reported for yttrium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data | |

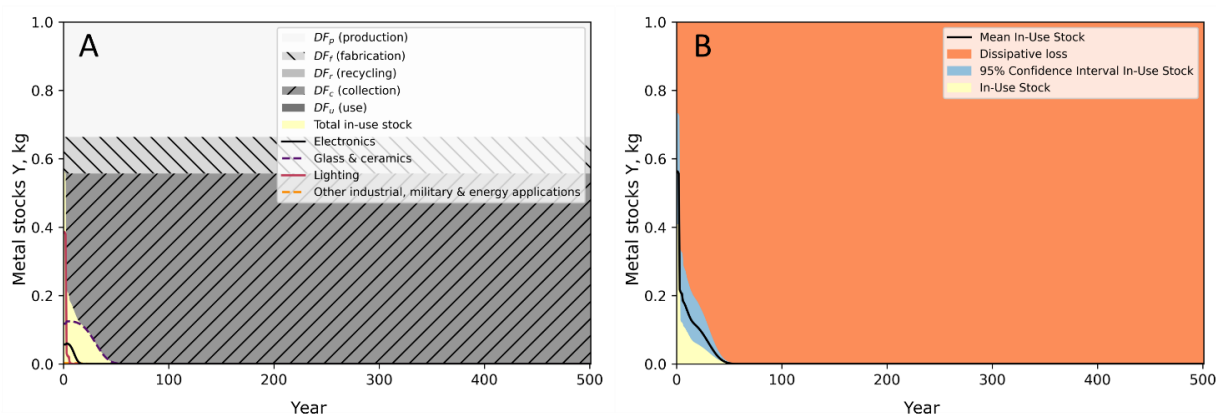


Figure B24. In-use stocks and losses of yttrium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.23 Zirconium**Table B32. Zirconium.**

| Zirconium | Zr, element number 40 | Uncertainty | | | | | | | | | | | | | | |
|--|---|-------------------------------------|----|-----------|----|------------------|-----|-------------------------------------|-----|--|----|---------------------|----|--------------|-----|---|
| End uses | <p>A majority of zirconium is used directly as minerals, i.e., zirconium silicate (ZrSiO4) and baddeleyite (ZrO2), with around 75% of its uses, while the remainder 25% is transformed in zirconium oxide and other chemicals including zirconium metal (European Commission, 2020c). Zirconium metal sponge represents only about 3% of zirconium uses, used mostly in the chemical process and nuclear energy industries (BRGM, 2018e; USGS, 2020). Major uses of zirconium include ceramics, foundry sand, opacifiers, and refractories (BRGM, 2018e; USGS, 2020).</p> <p>Several end-use distributions are available for zirconium: for 2008 (Graedel et al., 2013), 2011 (Zircon Industry Association, 2019a), 2012 (Iluka, 2014), 2015 (BRGM, 2018e; European Commission, 2020c) and 2019 (Zircon Industry Association, 2019b). Overall, the ceramics sector consumes around 50-60% of zirconium over the studied years. The latest distribution available is quite generic, and only values for ceramics (54%), foundries (14%) and refractories (11-14%) are provided. Therefore, we estimate the distribution based on other information available for prior years. Notably, the report of the Zircon Industry Association (2019a) provides the most disaggregated values out of the consulted studies.</p> <p>The use of zirconium metal for nuclear fuel cladding used in nuclear rods is aggregated in the Other miscellaneous category. ‘Chemicals’ are split between technical ceramics and gemstones (both aggregated in glass & ceramics category). ‘Other chemicals’, representing around 10% of end uses, are split even between the chemicals and Other miscellaneous categories to reflect the wide diversity of end-uses for such chemicals (cf. Zircon Industry Association, 2019a). Foundry sandcasting is aggregated to the metallurgical process sector. The following distribution is estimated to be representative of years 2015-2019:</p> <table><tr><td>Alloys & solders</td><td>1%</td></tr><tr><td>Chemicals</td><td>5%</td></tr><tr><td>Glass & ceramics</td><td>56%</td></tr><tr><td>Metallurgy & metalworking (process)</td><td>15%</td></tr><tr><td>Other industrial, military & energy applications</td><td>2%</td></tr><tr><td>Other miscellaneous</td><td>7%</td></tr><tr><td>Refractories</td><td>14%</td></tr></table> | Alloys & solders | 1% | Chemicals | 5% | Glass & ceramics | 56% | Metallurgy & metalworking (process) | 15% | Other industrial, military & energy applications | 2% | Other miscellaneous | 7% | Refractories | 14% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| Alloys & solders | 1% | | | | | | | | | | | | | | | |
| Chemicals | 5% | | | | | | | | | | | | | | | |
| Glass & ceramics | 56% | | | | | | | | | | | | | | | |
| Metallurgy & metalworking (process) | 15% | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 2% | | | | | | | | | | | | | | | |
| Other miscellaneous | 7% | | | | | | | | | | | | | | | |
| Refractories | 14% | | | | | | | | | | | | | | | |
| Production yield | <p>Zirconium is most commonly produced from heavy minerals enriched sand, with around 97% of its production (Zircon Industry Association, 2019a). Althaus et al. (2007) reported a combined concentration and beneficiation yield of 95%. Iluka, an important actor in the global production of zirconium, rather suggests losses of around 10% during the processing stage (Iluka, 2020), and of between 85-94% for their Hamilton and Narngulu mineral</p> | U1: 2 U2: 1 U3: 2 U4: 2 U5: 1 | | | | | | | | | | | | | | |

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| | <p>separation plants depending on the mineral concentrate source feed and product stream characteristics (Iluka, 2019). Therefore, we consider an average concentration and refining yield of 90%, and further assume extraction losses of 5%. The resulting production yield is estimated to be of 86%.</p> <p>There may be some cases where zirconium is extracted along, but not further processed, from other heavy mineral ores such as baddeleyite. These are not considered in this dataset. In some other cases, the zircon-enriched concentrate may be exported to processing plants in China for further processing (Zircon Industry Association, 2019a), alike for zirconium-bearing REE ores (see e.g. the case of the Nechalacho Rare Earth Elements Project discussed in section B.2.3.3.1). We assume such processes to have a similar yield to those reported above.</p> | |
| Fabrication and manufacturing | 95% (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | Although some new scraps of zirconium metal may be recycled (BRGM, 2018e), we estimate the global recovery of zirconium new scraps to be overall negligible (European Commission, 2020c). Thus, we assume possible losses to be included in the fabrication yield, and 0% is reported in this dataset. | U1: 2 U2: 1 U3: 1 U4: 3 U5: 1 |
| Remelting | We assume a remelting rate of 100% for zirconium metal and zircon; and all EOL losses are reported as collection losses. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | <p>Although zircon used for sandcasting may be recycled (Ciacci et al., 2015), we consider that it needs to be continuously replenished over time, and a dissipation in use rate of 100% is reported over an application lifetime of 1 year (cf. section B.2.2.3).</p> <p>A dissipation in use rate of 0% is reported for other applications, based on Ciacci et al. (2015).</p> | Per sector; please refer to Supplementary Data |
| Collection and sorting | Zirconium may be recycled from some steel alloys or refractory material (Ciacci et al., 2015; European Commission, 2020c; USGS, 2020). The USGS mentions that “spent or rejected zirconia refractories are often recycled”, and the European Commission (2020c) estimated that about 70% of refractory materials and alloys may be recycled. However, this rate likely includes a wide share of downcycling, especially in the case of refractories, as it is estimated to be the case for magnesia refractories (cf. Table B13). Without further available information, we assume a functional EOL-RR of 10% for zirconium refractories. Contrastingly, alloys are expected to be more easily recyclable into new metal products with similar functionality since it is mostly used in specialized applications, and we assume a collection rate of 50% for alloys and Other industrial applications. While there seems to be some potential for the recycling of zirconium alloys used for nuclear fuel cladding in the future (OECD Nuclear Energy Agency, 2018), it is estimated not to be recyclable currently. | Per sector; please refer to Supplementary Data |

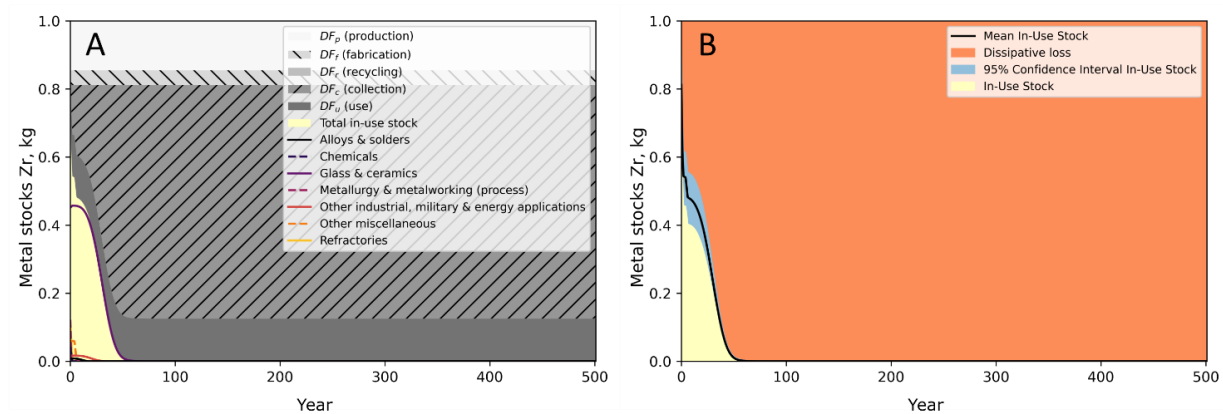


Figure B25. In-use stocks and losses of zirconium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.24 Niobium**Table B33. Niobium.**

| Niobium | Nb, element number 41 | Uncertainty |
|--|---|---|
| End uses | Several global end-uses of niobium are reported, e.g. for years 2004 and 2010 (Schwela, 2011), 2008, 2009 and 2010 (Nuss et al., 2014), 2014 (BRGM, 2016d), and 2017 (European Commission, 2020a). The latter is based on the sales of the largest niobium producer (CBMM) for that year; and a distribution is also available for 2018 (CBMM, 2018a). | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| | Around 90% niobium was consistently used in steels and alloys between 2004 and 2018. About 75% of niobium is used in steel production for a variety of microalloy and low-alloy steels to improve corrosion resistance, strength and toughness, amongst other properties. These steels are used mostly in pipelines, transportation, and structural applications (Schulz et al., 2017). Other niobium alloys are used in nickel-, cobalt-, and iron-base superalloys for high-temperature applications such as jet engine components, in superconducting magnets used in MRI, nuclear magnetic resonance instruments and particle accelerators (Schulz et al., 2017). It has recently started to be used as solid niobic acid that acts as a catalyst in the conversion of palm oil to biodiesel (Schulz et al., 2017). | |
| | The following end-use distribution is based on end-use data for 2018 (CBMM, 2018a), and is further refined with other available information. Other uses, representing 9% of niobium’s end-uses in 2018, are estimated to be split between catalysts (1%), cutting tools (carbides, 2%), large magnets (1%), superalloys (3%) and electronics, including magnets (2%) based on qualitative and quantitative information (BGS, 2011; BRGM, 2016d; European Commission, 2020a; Nuss et al., 2014). Pipelines are categorized as infrastructure. Heat-resistant stainless steels are classified in Other industrial, military & energy applications, given that their final distribution in end-uses is not precisely known. These could include e.g. uses by the petrochemical industry and power plants (Nuss et al., 2014). The following distribution is estimated to reflect global end-uses of niobium in 2018: | |
| | Alloys & solders | 3% |
| | Catalysts (homogenous & aggressive env.) | 1% |
| | Construction | 40% |
| | Cutting tools | 2% |
| | Electronics | 2% |
| | Infrastructure | 16% |
| | Magnets (large) | 1% |
| Other industrial, military & energy applications | 11% | |
| Transport | 24% | |
| Production yield | Extraction losses of 13% and processing losses of 16% are reported in Nuss et al. (2014), resulting in a production yield of 71%. | U1: 2 U2: 4 U3: 1 U4: 3 U5: 1 |

| | | |
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| Fabrication and manufacturing | <p>A CBMM's technical document for the addition of ferroniobium during steelmaking suggests that in optimal conditions, the recovery of niobium to the alloy should be above 95% (CBMM, 2018b). The remainder of niobium is expected to be lost to slags. Other losses from the fabrication and manufacturing of steel into end-use products is expected to follow similar trends to that of iron, for which a fabrication and manufacturing yield of 89% has been calculated, with a new scrap recovery of 100% (cf. Table B21). The MFA of niobium in the US in 1998 also suggests a fabrication yield of 89%, with a new scrap recovery of 94% (USGS, 2004b).</p> <p>Based on this information, we estimate that, in average, about 5% of primary niobium is lost to slags during steelmaking, and that an additional 5% of niobium is lost during other fabrication and manufacturing processes without further functional recovery. Given the potential discrepancies between the remelting rates of new and old scraps, the recycling of new scraps is estimated to be included in the fabrication and manufacturing yield (cf. Remelting box). The overall fabrication yield is estimated to be of 90%.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | New scrap recovery is integrated in the estimate of the fabrication yield. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | <p>EoL recycling rates of 50% and 56% have been reported for the US and globally, respectively (UNEP, 2011). Yet, while an important fraction of niobium may be collected and enter the recycling flow along with old steel scraps, the European Commission (2020a) estimated that only about 0.3% of niobium was functionally recycled. Indeed, the composition of old steel scraps is often not precisely known (UNEP, 2013). Similarly, Andersson et al. (2017) considered that the niobium content of EOL vehicle scraps that get recycled were non-functionally recycled, and that niobium was either lost to the carrier metal or to other materials. It is here considered that the recycling of niobium from old scraps is mostly non-functional. Furthermore, while some functional recycling of carbides may occur, they cover only a small fraction of total niobium uses; and were disregarded from the calculation of the remelting yield. Considering the collection rates reported below for niobium, we estimate the remelting yield to be of approximately 0.4%.</p> | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | <p>The dissipation in use rates from the most important niobium uses are thought to be negligible (Ciacci et al., 2015). Parts of niobium uses as catalysts and cutting tools (carbides) may be dissipated during use. For the latter, we report a dissipation in use of 5%, using the estimate reported for cobalt as a proxy, as done for e.g. tungsten (Ciacci et al., 2015). For catalysts, the latter authors report a dissipation in use rate of 2% using palladium catalyst losses as a proxy, which is also reported here.</p> | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>Collection rates of niobium-alloyed steel are assumed to be globally similar to iron, with a collection yield of 74% (cf. Table B21), and those of carbides, similar to that of tungsten (41%, cf. Table B61). Other uses are assumed not to be collected and separated for their niobium content. However, as discussed in the 'Remelting' box, the functional recycling of</p> | Per sector; please refer to Supplementary Data |

niobium contained in steel is estimated to be minimal, and thus these estimates have a minor influence of the results of the model.

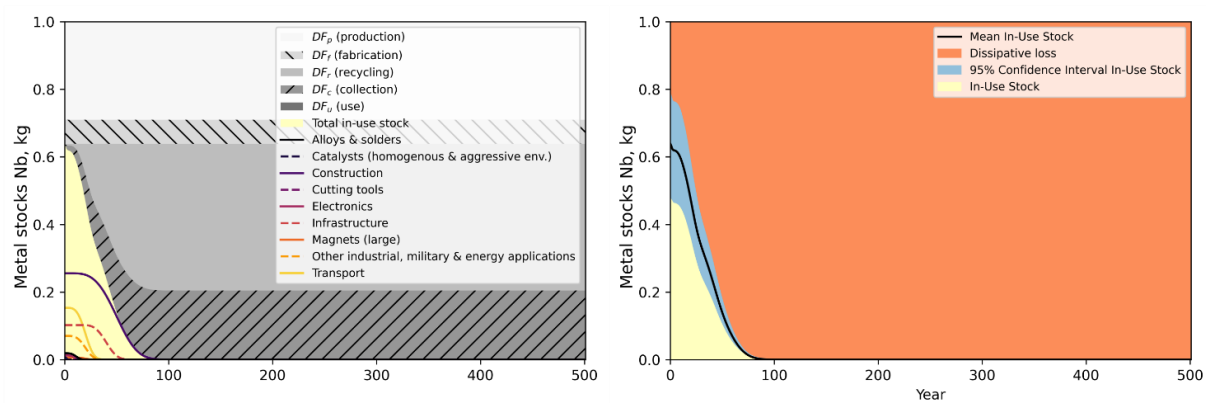


Figure B26. In-use stocks and losses of niobium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.25 Molybdenum**Table B34. Molybdenum.**

| Molybdenum | Mo, element number 42 | Uncertainty | | | | | | | | | | |
|---|---|---|----|--|----|--------------|-----|---------------|----|-------------|----|---|
| End uses | <p>Global end-uses of molybdenum are reported for years 2008 (Graedel et al., 2015), 2012 (Henckens et al., 2018, based on the International Molybdenum Association [IMoA]), and 2018 (IMoA, 2020).</p> <p>The most important uses of molybdenum are in engineering steels (42% of molybdenum use) and stainless steels (23%), both of which are used extensively in heavy machinery and infrastructure for the oil and gas industry (including pipelines) as well as other industries, large-scale transport (trains, ships) and construction (Graedel et al., 2015).</p> <p>Molybdenum is also used in cast iron (7%) for transportation, machinery and metal processing, as well as tool steels (7%), including high speed tool steels. Molybdenum metal and alloys (5%) are used in many specialty applications, many of which are heat resistant industrial components for high temperature processing (e.g., glass melting furnace electrodes, high temperature furnaces and heat exchangers) and heat resistant transport components (e.g., coatings for piston rings, molybdenum-rhenium alloys for rocket engines) (IMoA, 2020). Molybdenum superalloys (Ni alloys, with 3% of global molybdenum use) are highly corrosion-resistant and find extensive use in the chemical processing, pharmaceutical, oil & gas, petrochemical and pollution control industries (IMoA, 2020). Other important uses of molybdenum metal and alloys include lighting and various electronic devices (e.g., in power transistors, thin films and sputter targets) (IMoA, 2013). Molybdenum chemicals are also used in a range of non-metal applications such as catalysts, agricultural products and pigments (13% of total uses).</p> <p>In this dataset, end-uses reported by the IMoA (2020) are disaggregated based on quantitative and qualitative description of each end-use sectors provided by Ciacci et al., (2015), European Commission (2020c), Graedel et al. (2015), and IMoA (2013). Pipelines are included in the construction sector. Heat resistant materials are split into the mechanical equipment and transport sectors. Stainless steels are split between construction and industrial components. Various industrial components are categorized as mechanical equipment. Tools are split between cutting tools and mechanical equipment. Half of pigments & flame retardants category are attributed to plastic uses, and the remaining share of pigments are split into paint and ceramics. Moreover, it is estimated that about 4% of chemicals are used in inherently dissipative uses of type A or B (mostly agricultural products). The following end-use distribution for molybdenum is estimated to be representative of year 2018:</p> <table><tr><td>Agricultural & environmental applications</td><td>4%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>5%</td></tr><tr><td>Construction</td><td>41%</td></tr><tr><td>Cutting tools</td><td>2%</td></tr><tr><td>Electronics</td><td>1%</td></tr></table> | Agricultural & environmental applications | 4% | Catalysts (homogenous & aggressive env.) | 5% | Construction | 41% | Cutting tools | 2% | Electronics | 1% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| Agricultural & environmental applications | 4% | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 5% | | | | | | | | | | | |
| Construction | 41% | | | | | | | | | | | |
| Cutting tools | 2% | | | | | | | | | | | |
| Electronics | 1% | | | | | | | | | | | |

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|--------------------------------------|---|---|----|----------|----|----------------------|-----|-------|----|----------|----|-----------|-----|--|
| | <table><tr><td>Glass & ceramics</td><td>1%</td></tr><tr><td>Lighting</td><td>1%</td></tr><tr><td>Mechanical equipment</td><td>31%</td></tr><tr><td>Paint</td><td>1%</td></tr><tr><td>Plastics</td><td>2%</td></tr><tr><td>Transport</td><td>12%</td></tr></table> | Glass & ceramics | 1% | Lighting | 1% | Mechanical equipment | 31% | Paint | 1% | Plastics | 2% | Transport | 12% | |
| Glass & ceramics | 1% | | | | | | | | | | | | | |
| Lighting | 1% | | | | | | | | | | | | | |
| Mechanical equipment | 31% | | | | | | | | | | | | | |
| Paint | 1% | | | | | | | | | | | | | |
| Plastics | 2% | | | | | | | | | | | | | |
| Transport | 12% | | | | | | | | | | | | | |
| Production yield | Henckens et al. (2018) assumed a recovery of 80% from Mo ores and 40–45% recovery as a by-product from porphyry ores used for copper production, resulting in a production yield of 60%. These values are corroborated by other reported values reported in literature, for instance 47% recovery from porphyry ores (Ayres and Peiró, 2013) and 75–90% recovery from molybdenum ores (Roskill, 2020). Similarly, Graedel et al. (2015) reported 29% extraction losses and 13% other prefabrication losses for molybdenum. | U1: 3 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | <p>Scarce information is available for the yield of fabrication and manufacturing processes of molybdenum containing products. The USGS report aggregated losses for both steelmaking and fabrication processes (USGS, 2004b). Moreover, Nakajima et al. (2013) studied the flows of molybdenum in alloyed steels along with other alloying elements (Ni, Cr) in the Japanese economy in 2000. The reported yields for fabrication and manufacturing, new scrap recovery and remelting yields are estimated from these two references based on the following calculations and assumptions.</p> <p>Nakajima et al. (2013) mention that almost all of the scraps generated in the steel industry are recycled during the steel-making process, while scraps generated from the manufacturing of parts and accessories are relatively difficult to recycle. 7.4% losses of molybdenum are reported for the manufacturing of parts and accessories, suggesting that these new scraps are either not recovered, either that their molybdenum content is not functionally recycled. We here assume that these losses are mostly due to non-functional recycling given the 100% new scrap recovery rate reported in (USGS, 2004b).</p> <p>Both steelmaking and subsequent steps are covered in the fabrication and manufacturing process. However, melting losses from primary inputs to the steel melt are not easily identifiable, alike for other alloying elements such as niobium. We assume that downgraded steel as reported in (USGS, 2004b) results only from the remelting of new and old scraps, while new scrap generated originate from all of the material inputs to the fabrication process. Following this assumption, a yield of 83% is calculated from US statistics for 1998 (USGS, 2004b).</p> | U1: 2 U2: 4 U3: 2 U4: 3 U5: 1 | | | | | | | | | | | | |
| New scrap recovery | 100%, according to US statistics for molybdenum in 1998 (USGS, 2004b). This is consistent with the data for iron, for which a 100% rate has also been calculated (Helbig et al., 2020). However, it may be slightly overestimated given molybdenum uses in non-steel products. | U1: 2 U2: 4 U3: 2 U4: 2 U5: 1 | | | | | | | | | | | | |
| Remelting | A global EoL-RR of 20% is reported by Henckens et al. (2018), based on UNEP (2011) and USGS (2004b), while Graedel et al. (2015) reported an EoL-RR of 30% for all applications based on UNEP (2011). We here consider an | U1: 4 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |

| | | |
|-------------------------------|---|--|
| | <p>average EoL-RR of 25% across all molybdenum applications in order to estimate the collection and remelting yields.</p> <p>Since molybdenum consistently remains in the metal phase during recycling, it often becomes a contaminant rather than an alloying agent due to its involuntary addition to the melt (Ohno et al., 2014). USGS statistics suggest a melting yield of 89% from a mix of virgin materials, new scraps and old scraps during steelmaking, provided that downgraded steel is accounted for as non-functional recycling (USGS, 2004b). Assuming that losses from the melting process are mostly due to the share of new and old scraps in the melt (12 000 out of 25 300 mt), a remelting yield of 77% can be calculated.</p> <p>Moreover, Nakajima et al. (2013) reported 7.4% losses of molybdenum for the manufacturing of parts and accessories. Assuming a collection rate of 100% for new scraps, their data suggest functional remelting yield of 44% for these new scraps. This value is similar to the reported 69% of molybdenum unintentionally fed into the electric arc furnace during the EoL recycling of vehicles in Japan (Ohno et al., 2014). Based on this information, we roughly estimate a global functional remelting yield of 50%.</p> | |
| Dissipation in use | Based on Ciacci et al. (2015), we attributed the following dissipation in use rates to molybdenum end-use sectors: Agricultural & environmental applications (type A) and lubricants (type B), 100%; Catalysts, 5% (type B); Cutting tools, 5% (type B); Pigments (paint), 10% (using titanium as a proxy for paint use); and Other applications, 0%. | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>The collection yields are extrapolated accordingly with the following observations and assumptions. Plastic additives (pigments & smoke suppressants) are not readily recyclable, along with pigments used in paints and ceramics and dissipative uses of chemicals (Ciacci et al., 2015). These are attributed a collection rate of 0%. Moreover, the content of molybdenum in catalysts, lighting and electronics are less likely to be economically recyclable due to the overall low volumes and concentrations of molybdenum in final products, and are attributed a 0% collection yield as well.</p> <p>Thus, given the estimated remelting yield of 50% and global EoL-RR of 25%, an average collection yield of 55% is calculated for all of the other sectors. This yield is significantly lower than those reported for iron and its principal alloying elements, suggesting that the actual collection yields may be higher, and the remelting yield may be lower, than those reported in this dataset. This may warrant additional investigations of the global molybdenum flows, as also suggested by Henckens et al. (2018).</p> | Per sector; please refer to Supplementary Data |

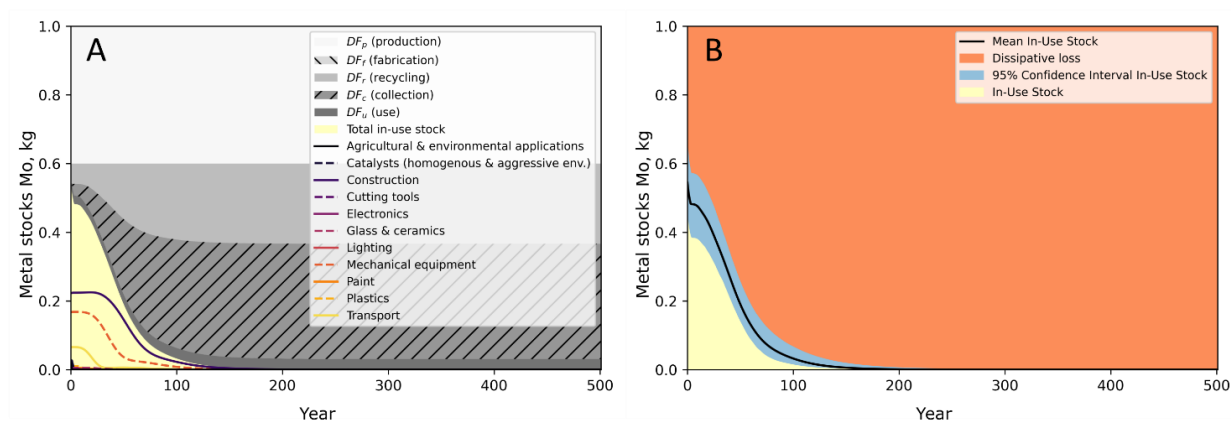


Figure B27. In-use stocks and losses of molybdenum over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.26 Ruthenium

Note: We used the catalysts category as a proxy for ruthenium-iridium anodes based on the reported lifetimes for this application to avoid generating additional single use sectors for industrial processes. The uses of ruthenium in the electrochemical industry (anodes coating) is reported in the Catalysts (heterogeneous & stable env.) sector, alike for iridium (cf. Table B64).

Table B35. Ruthenium.

| Ruthenium | Ru, element number 44 | Uncertainty |
|-------------------------------|---|---|
| End uses | Ruthenium is used as a process catalyst for a number of chemical processes such as ammonia production, for the coating of dimensionally stable anodes used by the chlor-alkali industry, in various electrical devices such as computer’s hard disks and as an alloying agent for various other applications such as aeronautics and dental crowns (BRGM, 2020c; Cowley, 2013; Graedel et al., 2013). Ruthenium’s end-uses are determined based on the average gross demand statistics for the year 2019 (Johnson Matthey, 2020b). For simplification purposes, the use of ruthenium anodes and catalyst applications are both classified as Catalysts (heterogeneous & stable env.). Those in the electrical industry are reported in electronics, and those reported as “other” are classified in the alloys category. The distribution, representative of year 2019, is the following: | U1: 2 U2: 1 U3: 1 U4: 3 U5: 2 |
| | Alloys & solders | 16% |
| | Catalysts (heterogeneous & stable env.) | 50% |
| | Electronics | 34% |
| Production yield | The mining yield is estimated to be 85% for all PGMs. The average concentration, smelting and refining yields for ruthenium correspond to the average values reported by Nassar (2013) and are of 77.5%, 96% and 99%, respectively. The resulting production yield is of 63%. | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 |
| Fabrication and manufacturing | It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for ruthenium. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | A remelting yield of 99% is assumed (same as refining). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | Based on Ciacci et al. (2015), it is considered that 5% of ruthenium used in the chemical industry is dissipated over its lifetime, and that 20% is dissipated in electrochemical applications over their lifetimes, resulting in a weighted average of 11% dissipation in use for the catalysts sector. Other uses are not considered to be dissipative. | Per sector; please refer to Supplementary Data |
| Collection and sorting | While UNEP (2011) estimated that between 5 and 15% of ruthenium was functionally recycled at its end-of-life, the BRGM more recently estimated a recycling rate of over 50% (BRGM, 2020c). Notably, the ruthenium content of catalysts and some uses in electronics (e.g., printed circuit boards, hard drives) is thought to be well recycled (BRGM, 2020c). | Per sector; please refer to Supplementary Data |

Assuming constant end-uses over time, the average of the EoL-RR values reported by Nassar (2013) suggest an average recycling yield of about 35% for ruthenium, which is significantly below the 50% suggested by the BRGM. The values suggested by the author are therefore updated, assuming that 35% of ruthenium in electronics is recycled rather than the reported 0 to 5%. The following collection yields are estimated: alloys, 15%; catalysts, 85%; and electronics, 15%.

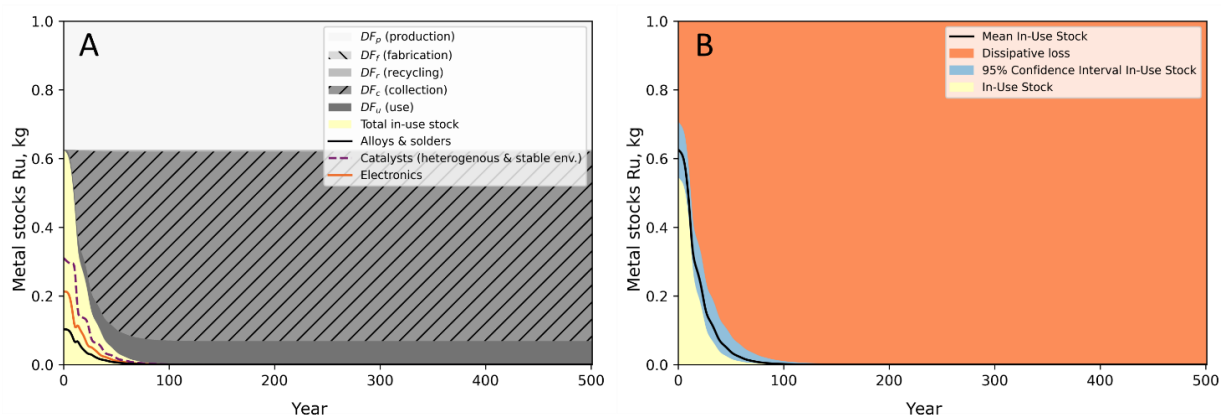


Figure B28. In-use stocks and losses of ruthenium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.27 Rhodium**Table B36. Rhodium.**

| Rhodium | Rh, element number 45 | Uncertainty | | | | | | | | | | |
|--|--|---|----|-------------|----|---------------------|----|--|----|-----------|-----|---|
| End uses | <p>Rhodium is largely used as a catalyst in car exhaust pipes to control NOx emissions (BRGM, 2018f; Graedel et al., 2013). It is also used by the chemicals and glass manufacturing industries, in electronic devices and motors, and in various other uses (BRGM, 2018f; Graedel et al., 2013). Rhodium’s end-uses are calculated based on the average gross demand statistics for the year 2019 (Johnson Matthey, 2020b). The following distribution is representative of the year 2019:</p> <table><tr><td>Catalysts (homogenous & aggressive env.)</td><td>6%</td></tr><tr><td>Electronics</td><td>1%</td></tr><tr><td>Glass manufacturing</td><td>5%</td></tr><tr><td>Other industrial, military & energy applications</td><td>2%</td></tr><tr><td>Transport</td><td>87%</td></tr></table> | Catalysts (homogenous & aggressive env.) | 6% | Electronics | 1% | Glass manufacturing | 5% | Other industrial, military & energy applications | 2% | Transport | 87% | U1: 2 U2: 1 U3: 1 U4: 3 U5: 1 |
| Catalysts (homogenous & aggressive env.) | 6% | | | | | | | | | | | |
| Electronics | 1% | | | | | | | | | | | |
| Glass manufacturing | 5% | | | | | | | | | | | |
| Other industrial, military & energy applications | 2% | | | | | | | | | | | |
| Transport | 87% | | | | | | | | | | | |
| Production yield | <p>The mining yield is estimated to be 85% for all PGMs.</p> <p>The average concentration, smelting and refining yields for rhodium correspond to the average values reported by Nassar (2013) and are of 77.5%, 96% and 98%, respectively. The resulting production yield is of 62%.</p> | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | |
| Fabrication and manufacturing | <p>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for rhodium.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | |
| New scrap recovery | <p>N/A; 0% reported in this dataset.</p> | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | |
| Remelting | <p>A remelting yield of 98% is assumed (same as refining).</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | |
| Dissipation in use | <p>About 2% of rhodium is estimated to be lost during use in exhaust pipes, 17.5% in its use as a catalyst for chemical production, and <1% in the glass manufacturing industry (Hagelüken, 2003; Nassar, 2013). The two former values are reported as such. However, Ciacci et al. (2015) estimated the loss to the glass production process to be of about 0.6% out of 8% used in that sector over a lifetime of 2 years, suggesting a dissipation in use rate of 8%. Based on this information, we assume an average dissipation in use rate of of 5% for to the glassmaking process over 2 years.</p> | Per sector; please refer to Supplementary Data | | | | | | | | | | |
| Collection and sorting | <p>Around 50-60% of the EoL rhodium scraps are recycled (BRGM, 2018f). The collection yields are calculated based on Nassar (2013) and UNEP (2011). For the rhodium content of auto catalysts, an average global EOL-RR of 50% is considered (UNEP, 2011). For the other yields, the average values of Nassar (2013) are considered and mostly match the estimated EOL-RR of UNEP (2011). Considering a remelting yield of 98%, the following collection yields are calculated: catalysts (homogenous & aggressive env.), 98%; electronics, 8%; glass manufacturing, 100%; other industrial, military & energy applications, 41%; and transport, 51%.</p> | Per sector; please refer to Supplementary Data | | | | | | | | | | |

Assuming a constant distribution of end-uses over time, these yields suggest a global EOL-RR of rhodium of approximately 55%, within the range recently reported by the BRGM, and are therefore estimated to be fairly representative of the current collection yields.

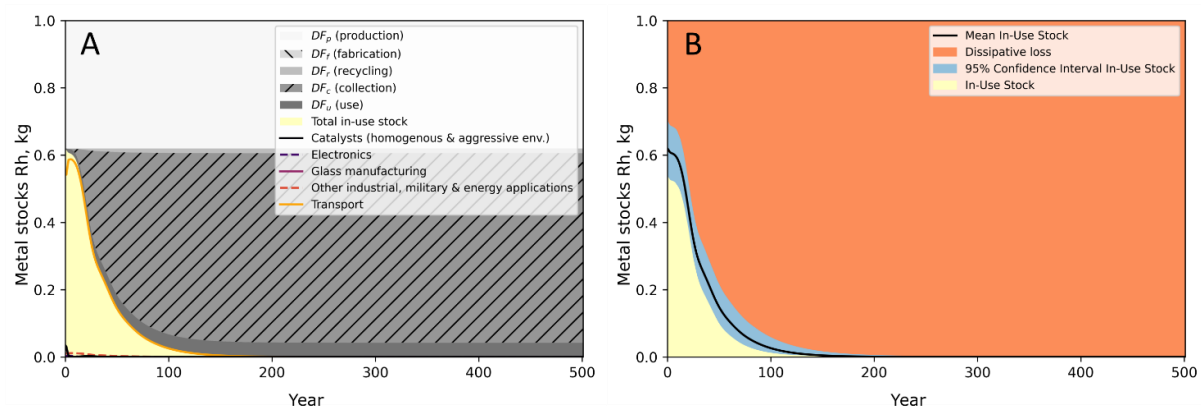


Figure B29. In-use stocks and losses of rhodium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.28 Palladium**Table B37. Palladium.**

| Palladium | Pd, element number 46 | Uncertainty | | | | | | | | | | | | |
|--|---|---|----|--|----|-------------|----|----------------------|----|--|----|-----------|-----|---|
| End uses | <p>Palladium is used in a range of applications, the most important being auto catalysts. Other applications include dentistry, jewelry, catalysts for the chemical and petroleum industries, as well as electronics (BRGM, 2017f; Graedel et al., 2013).</p> <p>The end-use distribution for palladium is calculated based on gross demand statistics published in Johnson Matthey’s reports (Johnson Matthey, 2020a, 2015). On average, palladium has been de-invested by approximately 1.3 ton per year over the past 10 years. A possible explanation for such phenomena is the important increase of palladium demand for car exhausts over the same period due to e.g. more demanding air quality regulation. Therefore, the investment category is neglected for palladium, and other end-uses are normalized to obtain a total distribution of 100%. The end uses, representative of 2019, are the following:</p> <table><tr><td>Biomedical & dental</td><td>3%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>5%</td></tr><tr><td>Electronics</td><td>6%</td></tr><tr><td>Jewelry & investment</td><td>1%</td></tr><tr><td>Other industrial, military & energy applications</td><td>2%</td></tr><tr><td>Transport</td><td>84%</td></tr></table> | Biomedical & dental | 3% | Catalysts (homogenous & aggressive env.) | 5% | Electronics | 6% | Jewelry & investment | 1% | Other industrial, military & energy applications | 2% | Transport | 84% | U1: 2 U2: 1 U3: 1 U4: 3 U5: 1 |
| Biomedical & dental | 3% | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 5% | | | | | | | | | | | | | |
| Electronics | 6% | | | | | | | | | | | | | |
| Jewelry & investment | 1% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 2% | | | | | | | | | | | | | |
| Transport | 84% | | | | | | | | | | | | | |
| Production yield | <p>The mining yield is estimated to be 85% for all PGMs.</p> <p>The average concentration, smelting and refining yields for palladium correspond to the average values reported by Nassar (2013) and are of 84.2%, 96% and 98.9%, respectively. The resulting production yield is 68%.</p> | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | <p>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). Minor losses are reported for jewelry (4%) and dental applications (3%) (Nassar, 2013). A yield of 100% is considered for other applications, resulting in an average yield of 99.9% for palladium.</p> | U1: 2 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |
| New scrap recovery | <p>The recovery of new scrap is considered to be included in the fabrication and manufacturing yield, and a new scrap recovery yield of 0 % is reported in this dataset.</p> | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | |
| Remelting | <p>A remelting yield of 98.9% is assumed (same as refining).</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |
| Dissipation in use | <p>About 2% of palladium is estimated to be lost during use in exhaust pipes, and 24% from catalyst used in the chemical industry (Nassar, 2013).</p> | Per sector; please refer to Supplementary Data | | | | | | | | | | | | |

| | | |
|-------------------------------|--|--|
| Collection and sorting | <p>The EoL-RR of palladium is estimated to be between 60 and 70%, about 80% of which results from the recycling of catalysts contained in car exhausts, and the remainder mostly from electronic waste (BRGM, 2017f). We estimate average collection yields based on Nassar (2013) and UNEP (2011). Considering the important shares of EOL recycling from auto catalysts and electronic wastes, the current global EOL-RR are estimated to be of 60% and 20%, respectively. These estimates are both slightly higher than the estimates of UNEP (2011) around 2010. The following collection yields are calculated considering a remelting yield of 98.9%: Catalysts, 98%; Electronics, 22%; Jewelry & investment, 96%, Transport, 81%; Biomedical & dental, 18%; and Other industrial, military & energy applications, 18%. Assuming a constant distribution of end-uses over time, these values suggest a global EOL-RR of approximately 60%, and are estimated to be representative of the current recycling yields.</p> | Per sector; please refer to Supplementary Data |
|-------------------------------|--|--|

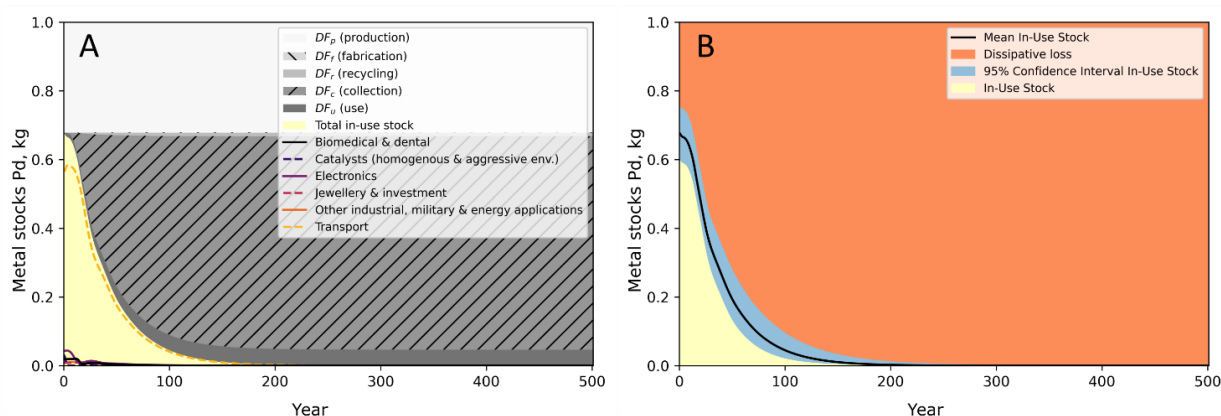


Figure B30. In-use stocks and losses of palladium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.29 Silver**Table B38. Silver.**

| Silver | Ag, element number 47 | Uncertainty |
|-------------------------------|--|---|
| End-uses | The Silver Institute provides yearly demand data for silver since 1991 in their yearly surveys. Demand data for the year 2018 is considered (The Silver Institute, 2019). It is chosen over the 2019 distribution since industrial applications of silver were disaggregated in a more transparent display. Alike for other investment products, the relative share of silver used in this end-use category is adjusted using a 10-years average to reflect the changes in demand due to the economic conjuncture (cf. method for other precious metals, section B.2.3.2). Silver catalysts for the production of ethylene oxide are classified as catalysts (homogenous & aggressive env.), considering that these catalysts are estimated to have a lifetime of between 18 and 36 months before they need to be regenerated (The Silver Institute, 2019). Brazing alloys and solders are categorized as alloys. Coins and bars, silverware as well as jewelry are aggregated in jewelry & investment. Finally, 1% out of the other “other” category reported by the Silver Institute is considered to be used as chemicals used in dispersive applications (food hygiene, detox chemicals, etc.), based on Ciacci et al. (2015). The following distribution is estimated to be representative of the year 2018: | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| | Alloys & solders | 6% |
| | Catalysts (homogenous & aggressive env.) | 1% |
| | Chemicals | 1% |
| | Electronics | 24% |
| | Jewelry & investment | 43% |
| | Other industrial, military & energy applications | 13% |
| | Photography | 4% |
| | Solar cells | 8% |
| Production yield | 84% (Helbig et al., 2020, based on Johnson et al., 2005) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Fabrication and manufacturing | 91% (Helbig et al., 2020, based on Johnson et al., 2005) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| New scrap recovery | 100% (Helbig et al., 2020, based on Johnson et al., 2005) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Remelting | 100% (Helbig et al., 2020, based on Johnson et al., 2005) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | Dissipation rates of 100% are reported for chemicals , and 0% for other applications (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |

| | | |
|-------------------------------|---|---|
| Collection and sorting | <p>Helbig et al. (2020) calculated an average collection yield of 57% based on Johnson et al. (2005). We here consider the sector-specific EOL-RR for five out of seven categories representing the main silver uses reported by Nassar et al. (2012), based on Graedel et al. (2011). The following EOL-RR are estimated to represent collection yields, considering the reported remelting yield of 100%: alloys, 50%; electronics, 12.5%; jewelry & investment, 95%; photography, 50%; Other industrial, military & energy applications, 50%.</p> <p>The silver catalysts used for ethylene oxide production are thought to be well recycled and represented half of the recycled silver from industrial applications in 2014 (BRGM, 2017g). The Silver Institute (2019) reported that approximately 2% of the silver content of catalysts is lost during the recovery process. Based on this information, we estimate a collection yield of 95% for catalysts, aligning on the higher estimates for other silver applications.</p> <p>Silver used in solar cells is a recent application, and the in-use stock of solar panels is growing rapidly while few solar panels have reached end-of-life (Latunussa et al., 2016). While this dataset is by no means prospective, we assume that 10% of the silver content would be readily functionally recycled currently given the technical and economic feasibility of recovering silver from panels (see e.g. Fangeat et al., 2020; Latunussa et al., 2016; Markert et al., 2020; and Suzy et al., 2020). Considering the remelting yield of 100%, a collection yield of 10% is reported for this application.</p> | <p>Per sector; please refer to Supplementary Data</p> |
|-------------------------------|---|---|

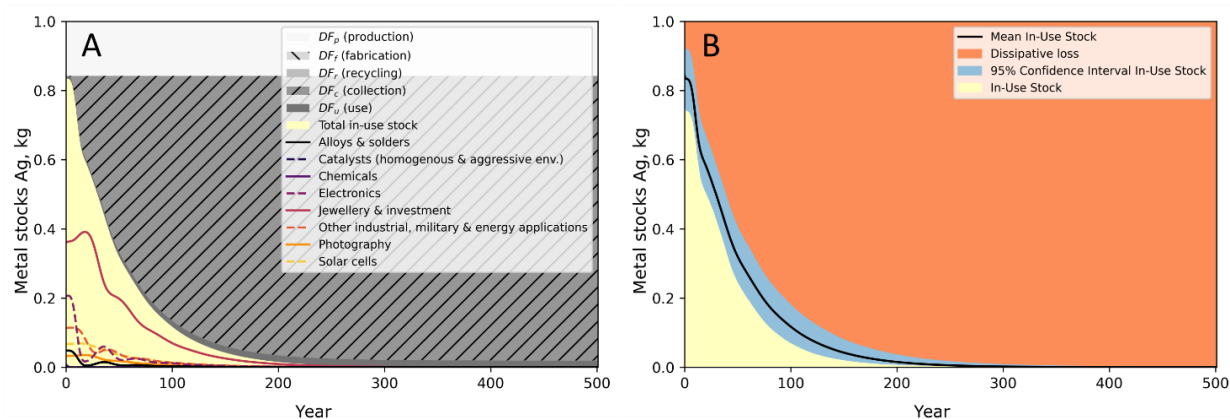


Figure B31. In-use stocks and losses of silver over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.30 Cadmium**Table B39. Cadmium.**

| Cadmium | Cd, element number 48 | Uncertainty | | | | | | | | | | | | |
|--|--|--|-----|----------------------------------|-----|------------------|----|--|----|----------|----|---------------------|----|---|
| End uses | <p>Global end-uses of cadmium are reported for years 2003 (Harper et al., 2015), 2008 (USGS, 2009) and 2018 (BRGM, 2019b). These distributions are similar to the Europe end-uses in between 2012 and 2016 (European Commission, 2020c). Although cadmium is used increasingly in solar cells, their share remains small in comparison to total cadmium uses (BRGM, 2019b).</p> <p>Values reported for 2018 (BRGM, 2019b) are disaggregated based on reported values for previous years. It is assumed that 20% of batteries are used in industrial applications, and the rest in user batteries (Graedel et al., 2013; Harper et al., 2015). Given the multiple potential uses for pigments (ceramics, plastics, paints, inks, etc.) for which lifetimes ranging from approximately 8 to 22 years are reported (Cha et al., 2013; Hawkins et al., 2006; Matsuno et al., 2012), these are split half and half between the plastics and the glass and ceramics sectors to reflect the diversity of potential applications. The plastics sector also includes stabilizers. The following distribution for global end-uses is estimated to be representative for years circa 2018:</p> <table><tr><td>Batteries (consumer electronics & lead acid)</td><td>64%</td></tr><tr><td>Batteries (utility & industrial)</td><td>16%</td></tr><tr><td>Glass & ceramics</td><td>5%</td></tr><tr><td>Other industrial, military & energy applications</td><td>1%</td></tr><tr><td>Plastics</td><td>6%</td></tr><tr><td>Protective coatings</td><td>8%</td></tr></table> | Batteries (consumer electronics & lead acid) | 64% | Batteries (utility & industrial) | 16% | Glass & ceramics | 5% | Other industrial, military & energy applications | 1% | Plastics | 6% | Protective coatings | 8% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| Batteries (consumer electronics & lead acid) | 64% | | | | | | | | | | | | | |
| Batteries (utility & industrial) | 16% | | | | | | | | | | | | | |
| Glass & ceramics | 5% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 1% | | | | | | | | | | | | | |
| Plastics | 6% | | | | | | | | | | | | | |
| Protective coatings | 8% | | | | | | | | | | | | | |
| Production yield | <p>Cadmium is naturally present as a trace element in multiple raw materials such as gypsum, phosphates, iron, copper and lead ores, and coal, though primary cadmium is most typically produced as a by-product of zinc (BRGM, 2019b; Hawkins et al., 2006; Kwonpongsagoon et al., 2007). We here consider only that part of cadmium that originates from zinc/lead ores as potential cadmium resources.</p> <p>Harper et al. (2015) report 6% mining losses and 5% refining losses based on US values in 1989 (Llewellyn, 1994). A mining and beneficiation yield of 77%, and refining yield of 83% can be calculated for Australia in the fiscal year of 1998-1999 (Kwonpongsagoon et al., 2007). Wang et al. (2018) report a 77.8% mining yield based on Cha et al. (2013); however, we could not replicate the calculation and the value is not considered in the dataset. A production yield of 76% is estimated from the average yields for Australia and the US.</p> | U1: 2 U2: 4 U3: 3 U4: 2 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | Fabrication yields are reported to be of nearly 100% (Cha et al., 2013; Plachy, 2003), which seems likely given the high toxicity of cadmium and the associated regulations. Based on these references, the fabrication | U1: 3 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | |

| | | |
|-------------------------------|---|---|
| | <p>rate is estimated to be of 99.8% in this dataset, including the potential recovery of new scraps.</p> <p>It can be observed that Hawkins et al. (2006) report cadmium emissions to air, water and “other releases” from smelting, manufacturing and recycling operations in the US, that suggest that some industries such as those producing plastics and coatings could have lower fabrication yields than these. However, it is not specified whether emissions result from a voluntary use of cadmium (i.e. cadmium resources) or not, nor how “other releases” are handled (cf. Hawkins et al., 2006, table 2). Therefore, these data are disregarded, but could warrant additional investigations.</p> | |
| New scrap recovery | The recovery of new scraps is assumed to be covered in the fabrication and manufacturing yield. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | <p>The recycling yield of collected scraps is believed to be nearly 100% based on values reported for the US (Plachy, 2003), Japan (Matsuno et al., 2012), and Korea (Cha et al., 2013).</p> <p>Up to 95% for cadmium telluride semiconductors used in photovoltaic cells is thought to be recyclable (BRGM, 2019b; Cha et al., 2013). Given that batteries are the main source of secondary cadmium, which is reported as “almost 100% recyclable” when collected (European Commission, 2020c), and that photovoltaics represent a small share of total cadmium end-use (< 1%), a remelting yield of 100% is estimated.</p> | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | Around 20% of cadmium is estimated to be emitted from coatings during use (Ciacci et al., 2015). While small amounts of cadmium could also be emitted from solar panels (Cha et al., 2013), they are assumed to be negligible, and 0% dissipation in use is reported for all other applications. | Per sector; please refer to Supplementary Data |
| Collection and sorting | A large majority of the functional recycling of cadmium occurs from batteries (Ciacci et al., 2015; European Commission, 2020c). Collection yields are reported accordingly with the estimates for the 2001-2008 period of Harper et al. (2015). The EoL-RR is estimated to correspond to the collection yield, given that a remelting yield of 100% is reported for cadmium. These yields are of 20% for consumer batteries, 90% for industrial batteries, and of 0% for all other applications. | Per sector; please refer to Supplementary Data |

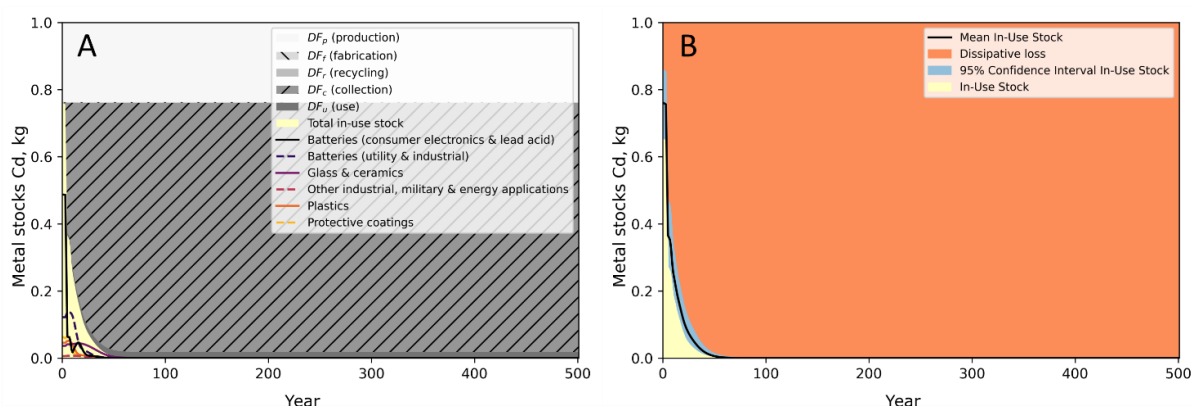


Figure B32. In-use stocks and losses of cadmium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.31 Indium**Table B40. Indium.**

| Indium | In, element number 49 | Uncertainty |
|------------------|--|---|
| End-uses | Global end-use distributions of indium are available for the years 2008 (Harper et al., 2015), 2010 (Peiró et al., 2013), 2011 (Licht et al., 2015) and 2012 (BRGM, 2017h; Lokanc et al., 2015). The main end-use of indium is as a transparent conducting oxide in the form of indium-tin oxide (ITO), mostly used for flat panel displays. Thin-film coatings may also be used for various glass products (e.g., architectural glass, EMI glass, etc.). Another important emerging use of indium is in copper-indium-gallium-diselenide (CIGS) solar panels (Lokanc et al., 2015). In this dataset, we consider the 2012 distribution of indium (BRGM, 2017h; Lokanc et al., 2015). A few refinements are made based on the end-use distribution of indium into semi-products and final products reported by Peiró et al. (2013) as well as Licht et al. (2015). First, alloys are disaggregated in dental, printed circuit boards (PCB)s and other alloys based on Licht et al. (2015). Dental uses and other alloys are reported as such, and PCBs are aggregated in the electronics category. Moreover, it is estimated that 2% of the global consumption of indium is for lighting applications based on the 2010 end-uses of indium (Peiró et al., 2013), and another 2% is considered to be used in various glass products. Thermal interface materials, representing 6% of the uses of indium, are assumed to be split equally between electronics and “Other miscellaneous” categories in order to reflect the diversity of applications for these materials. The following distribution is estimated to be representative of indium end-uses circa 2010-2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 2 |
| | Alloys & solders | 13% |
| | Batteries (consumer electronics & lead acid) | 5% |
| | Biomedical & dental | 0% |
| | Electronics | 59% |
| | Glass & ceramics | 2% |
| | Lighting | 2% |
| | Other industrial, military & energy applications | 8% |
| | Other miscellaneous | 3% |
| | Solar cells | 8% |
| Production yield | While the MFA of Licht et al. (2015) suggest a production yield of 54% (Helbig et al., 2020), it includes the reprocessing of zinc ore tailings in China. Other sources suggested that the actual recovery of primary indium may be lower. The Indium Corporation estimates that, in recent years, “no more than 50% of the indium mined every year is being extracted and refined as indium metal” (Mikolajczak and Peng, 2018). Similarly, citing a 2009 study by Mikolajczak, the National Renewable Energy Laboratory reported that approximately 30% of indium mined annually became refined indium metal, while their own in-depth investigation suggested that the recovery rate may be as low as 15-20% | U1: 3 U2: 1 U3: 1 U4: 3 U5: 2 |

| | | |
|--------------------------------------|--|---|
| | (Lokanc et al., 2015). Based on this information, we estimate the production yield of indium to be of approximately 30%. | |
| Fabrication and manufacturing | 13% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| New scrap recovery | 78% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| Remelting | 96% (Helbig et al., 2020, based on Licht et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 2 |
| Dissipation in use | Dissipative uses reported by Licht et al. (2015) consist in type C dissipation (i.e. indium alloys and PCBs); as such, they are considered to be unrecyclable rather than dissipated during use. Moreover, while Ciacci et al. (2015) estimate an in-use dissipation rate of 5% for indium tin oxides used in thin film coatings, these are reported to be process losses and are assumed to be taken into account in the fabrication and manufacturing and new scrap recovery yields. Dissipation in use from other indium applications are expected to be negligible, and a rate of 0% is reported for all applications. | Per sector; please refer to Supplementary Data |
| Collection and sorting | The EoL-RR of indium is reported to be null or negligible (BRGM, 2017h; Harper et al., 2015; Lokanc et al., 2015). Unlike for silver, the EOL recycling of indium from solar cells is estimated not to be feasible currently (Lokanc et al., 2015). Thus, a 0% collection rate is reported for all indium applications. | Per sector; please refer to Supplementary Data |

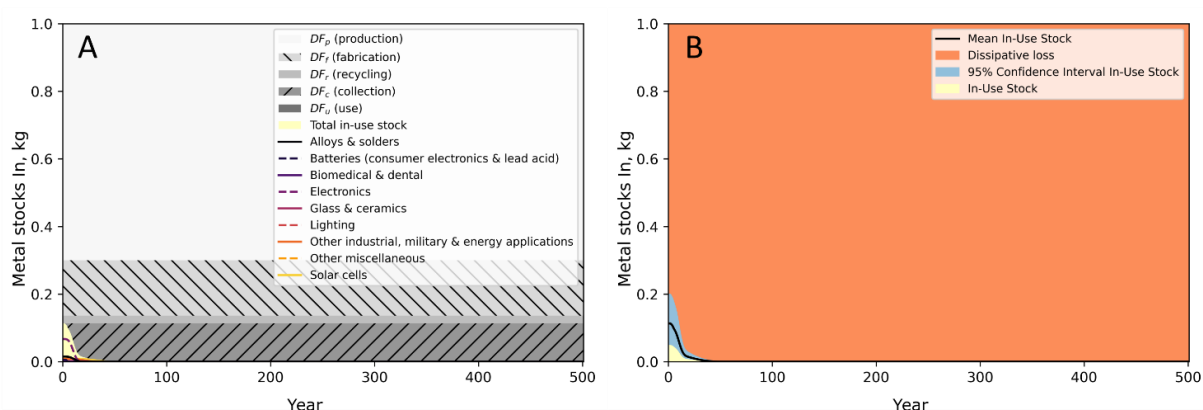


Figure B33. In-use stocks and losses of indium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.32 Tin**Table B41. Tin.**

| Tin | Sn, element number 50 | Uncertainty |
|-------------------------------|--|---|
| End-uses | Many end-use distributions of tin are reported in the literature, often based on the International Tin Research Institute. For example, end-use distributions are available for the years 2008 (Harper et al., 2015), 2007, 2010 and 2014 (Yang et al., 2017) and 2017 (European Commission, 2020c). | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| | The most important use of tin is consistently as solders over the studied years, with approximately half of its consumption. Other important uses include chemicals, lead acid batteries and as tinplate for packaging. It is also alloyed with copper to produce brass and bronze. For this dataset, we consider the most recent distribution for the year 2017 (European Commission, 2020c), which is refined using other available information. About 85% of tin solders are used in electronic appliances, and the rest in various industrial applications (European Commission, 2020c). Hence, 85% of the 47% reported use in solder applications are categorized in electronics, and the remaining 15% is reported in Other industrial, military & energy applications. Tinplate is disaggregated between packaging and tinning applications using a 15:2 ratio (Ciacci et al., 2015). Moreover, 2% out of the 10% others are reported as glassmaking process (floating glass process) (BRGM, 2017i). Brass and bronze are used mostly in transport and construction applications (Ciacci et al., 2015): these are assumed to be split half and half between the two sectors. The following distribution is estimated to be representative of the year 2017: | |
| | Batteries (electric vehicle) | 6% |
| | Chemicals | 6% |
| | Construction | 3% |
| | Electronics | 40% |
| | Glass manufacturing | 2% |
| | Other industrial, military & energy applications | 15% |
| | Packaging | 11% |
| | Plastics | 12% |
| | Protective coatings | 2% |
| Transport | 3% | |
| Production yield | 88% (Helbig et al., 2020, based on Izard and Müller, 2010) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 |
| Fabrication and manufacturing | 99% (Helbig et al., 2020, based on Izard and Müller, 2010) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 |
| New scrap recovery | 26% (Helbig et al., 2020, based on Izard and Müller, 2010) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 |

| | | |
|-------------------------------|--|---|
| Remelting | 100% (Helbig et al., 2020, based on Izard and Müller, 2010) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 |
| Dissipation in use | The use of tin in glass manufacturing is thought to be partly dissipative, with about 3200 tons out of 7100 tons of tin consumption for this application being reported as a consequence of losses during the production process (International Tin Association, 2017). Thus, we estimate an approximate 40% yearly dissipation rate for tin in this application, which results in about 64% of tin being lost over an average lifetime of 2 years. Some tin chemicals are used as biocides which are assumed to be used dissipatively (Ciacci et al., 2015): a dissipation rate of 100% is reported for chemicals. Other tin applications are not considered to be dissipative (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>Helbig et al. (2020) reported an average collection yield of 20% based on Izard and Müller (2010). This yield seemingly results mostly from the recycling of brass and bronze used in transport and construction, for which EoL-RR of 70% is reported by Harper et al. (2015), also based on Izard and Müller (2010). Contrastingly, UNEP (2011) reported a global EoL-RR of tin above 50%, referring to the recycling rate of tin in the US in 1998 (USGS, 2004a), i.e. before tin solders started to be widely used as solder in electronics (PCBs).</p> <p>When collected, tin used in packaging or plating is expected to be mostly lost to steel flows (Ciacci et al., 2015; Izard and Müller, 2010). We here report such losses with a collection yield of 0% for these applications, although it should be acknowledged that the same losses could potentially be considered as remelting losses. Moreover, Izard and Müller (2010) mention that it is difficult to track the fate of post-consumer electronic waste. Some tin solders used in electronics are effectively collected as part of electronics waste collection schemes and can theoretically be recycled, as many processes exist to do so (Yang et al., 2017). We estimate that 20% of tin contained in electronics is effectively collected and recycled. In order to approximate the life cycle of tin used in the floating glass process, we report a 100% collection yield for that application. While it is not an ideal modelling choice, it allows to prevent creating an additional end-use sector, and is expected to have a minor influence on the results of the model given its small application share. Collection yields of 0% are reported for all other tin applications.</p> | Per sector; please refer to Supplementary Data |

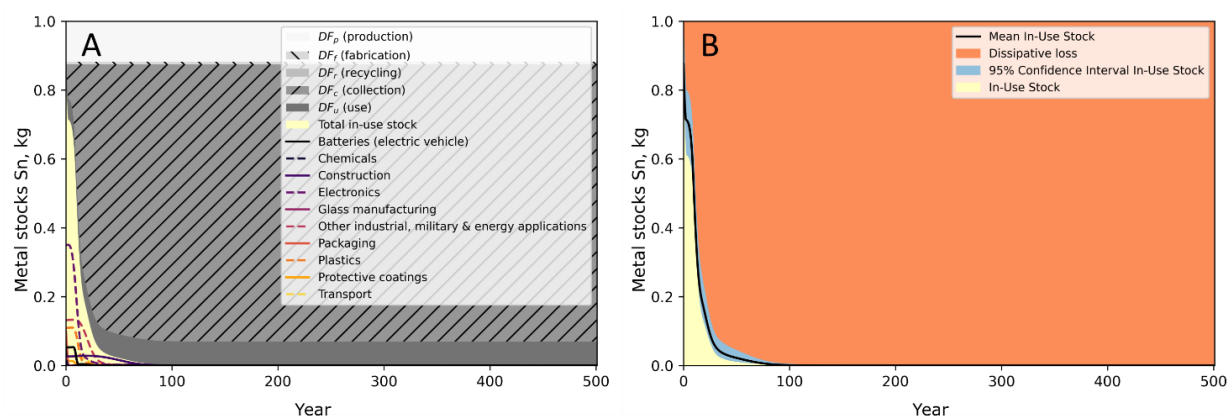


Figure B34. In-use stocks and losses of tin over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.33 Antimony**Table B42. Antimony.**

| Antimony | Sb, element number 51 | Uncertainty |
|------------------|--|---|
| End uses | Antimony is mostly used as a flame retardant (around 50%) and in lead acid batteries (around 25%). Another important use of antimony (approximately 6%) is as a catalyst in the production of PET polymers. Global end-uses are reported for the years 2008 (Panousi et al., 2016), 2010 (Dupont et al., 2016) and 2011 (BRGM, 2015b; Haarman, 2015). Although they are aggregated differently across references, the reported values are almost identical across these references, with the exception of an important decrease of antimony use in glass products between 2008 and 2010-2011 values. This matches the yearly -20% end-use trend observed for this application between 2000 and 2010, as measured by Dupont et al. (2016). | U1: 2 U2: 3 U3: 1 U4: 1 U5: 2 |
| | Out of the 52% end-use of antimony as a flame retardant, around 70% are thought to be used for electronic appliances (Dupont et al., 2016). The remaining 30% of flame retardants are seemingly used mostly in automotive (including aircrafts) components, rubber, PVC products used in construction, and textiles (Carling, 2006; Dupont et al., 2016; Haarman, 2015; Mathys et al., 2007; USGS, 2020). These 30% are thus disaggregated in 40% automotive, 40% construction and 20% “others” sectors following the works of Haarman (2015), p. 49-50. Finally, 2% of antimony used in alloys is assumed to be used for bullets and is classified in the other punctual applications. The following distribution is estimated to be representative of years circa 2011, based on BRGM (2015b), Dupont et al. (2016), and Haarman (2015): | |
| | Alloys & solders | 10% |
| | Batteries (consumer electronics & lead acid) | 26% |
| | Catalysts (homogenous & aggressive env.) | 6% |
| | Construction | 6% |
| | Electronics | 37% |
| | Glass & ceramics | 2% |
| | Other industrial, military & energy applications | 4% |
| | Other punctual applications | 2% |
| | Plastics | 1% |
| | Transport | 6% |
| Production yield | National MFAs of antimony are available for the US in 2000 (Carling, 2006), Switzerland in 2001 (Mathys et al., 2007) and China in 2013 (Chu et al., 2019). Some information on the SFA of antimony for Japan between 1970 and 2015 (including prospective estimates) is also available (Tsunemi and Wada, 2008). Moreover, a well-documented master’s thesis investigating the global anthropogenic cycle of antimony is available (Haarman, 2015). | U1: 3 U2: 1 U3: 1 U4: 2 U5: 1 |

| | | |
|--------------------------------------|---|-------------------------------------|
| | <p>Antimony can be produced as the main product from antimony ores, or as a by-product from gold, lead or zinc (BRGM, 2015b; Dupont et al., 2016). While copper ores are not used to produce antimony, they contain traces of antimony which could be recovered (Dupont et al., 2016). In this dataset, we consider only the voluntary recovery of antimony from antimony-bearing ores. This value could be revised if the recovery yields from gold, lead and zinc production (and eventually, copper) are considered. However, these are disregarded due to the lack of data, and the toxicity of antimony which limits its potential applications.</p> <p>Chinese is the most important antimony producer with over 50% of the production in the recent years (USGS, 2020). Based on an SFA of antimony in China in 2013 (Chu et al., 2019), a production rate of 78.8% can be calculated. Panousi et al. (2016) consider an extraction efficiency of 90% and a refining of 90% as well, resulting in a 81% estimated yield for production. The data reported in Haarman (2015) suggest a primary production yield of 89% for the year 2011. An average yield of 83% is considered in this dataset.</p> | |
| Fabrication and manufacturing | <p>A global yield of 96% can be calculated with the data of Haarman (2015). For metal products, Haarman estimated fabrication and manufacturing emissions and waste values based on a study for the lead anthropogenic cycle (Mao et al., 2008b), and for non-metallic products, based on European risk report for antimony trioxide (EU RAR, 2008). A similar yield of 95% is reported for the US for year 2000 (Carling, 2006).</p> <p>Contrastingly, the Chinese SFA for the year 2013 suggest a yield of roughly 60%, out of which most losses are considered as unrecovered waste or emissions (Chu et al., 2019). However, this value is extrapolated from the quantity of antimony used in manufactured products in China from other literature, and it suggests net manufacturing yields (including new scrap recovery) that are well below those of e.g. lead products used in the same manufacturing processes (Mao et al., 2008b). We could not find a reasonable explanation or additional evidence for such a low yield in the literature, and the value is disregarded in the dataset.</p> <p>Therefore, it is considered that 96% was the best available global estimate for the fabrication and manufacturing yield, based on Haarman (2015). The values from this same reference are considered to be most representative of global yields for other post-production processes as well given the exhaustively collected underlying data.</p> | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 |
| New scrap recovery | 29%, calculated based on Haarman (2015) | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 |
| Remelting | 83%, calculated based on Haarman (2015) | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | Some uses of antimony such as in ammunitions, and lubricating agents used in brake pads, can be dissipative (type B) (Ciacchi et al., 2015). | Per sector; please refer to |

| | | |
|-------------------------------|---|---|
| | <p>Ammunitions are reported to be used dissipatively. Other potentially dissipative applications are assumed to represent a negligible share of end use, and consequently of dissipation in use of antimony. Moreover, some antimony contained in catalysts for PET production is known to be lost to the PET. We roughly estimate that 66% of antimony is dissipation in use (type B) in PET catalysts over their lifetime, based on Ciacci et al. (2015).</p> | Supplementary Data |
| Collection and sorting | <p>Based on our literature survey for antimony, secondary antimony is thought to provide about 15-20% of total antimony supply, approximately 80% of which originates from old scraps. Of old scraps containing antimony, only lead acid batteries are considered to be functionally recyclable (Ciacci et al., 2015). Antimony contained in recycled batteries is thought to be mostly functionally recycled in new antimonial lead (Dupont et al., 2016). Therefore, we only consider the recovery of lead acid batteries for the calculation of functional recycling. In 2011, about 90% of lead acid batteries were recycled in Europe, and approximately 70% were thought to be recycled worldwide (Haarman, 2015). Based on this information and on the collection yield reported for lead used in these same batteries (i.e. 85%; cf. Table B69), a collection yield of 85% is estimated for antimony used in lead acid batteries. While this yield is much higher than the 20% EoL-RR reported by Panousi et al. (2016), it can be explained by the sharp trend noted for the recycling of antimonial lead over the past two decades (cf. Table B69).</p> | Per sector; please refer to Supplementary Data |

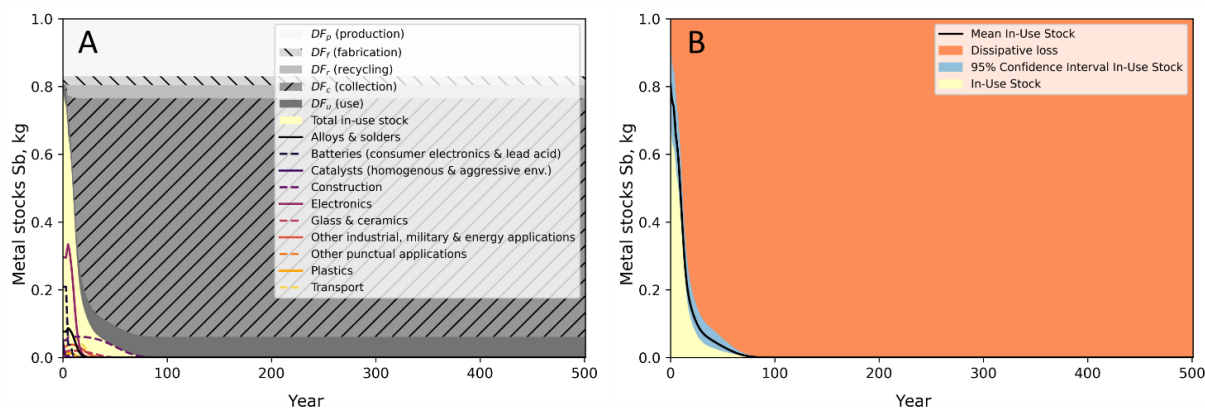


Figure B35. In-use stocks and losses of antimony over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.34 Tellurium**Table B43. Tellurium.**

| Tellurium | Te, element number 52 | Uncertainty | | | | | | | | | | | | |
|--|---|-------------------------------------|-----|-------------|-----|--|----|-----------------------------|----|--------|----|-------------|-----|---|
| End-uses | <p>Several estimates of the global end-use distributions of tellurium are available from the USGS Mineral Commodity Summaries, including years from 2014 to 2019. The latest distribution for 2019 is used (USGS, 2020). The reported end-use distribution is the same as those for the years 2015-2018 and that of 2010 published by Ciacci et al. (2015), also based on the USGS. Tellurium’s most important uses are for cadmium-tellurium solar cells and thermoelectric devices. The latter are aggregated in the electronics category. Metallurgical uses include stainless steel and copper alloys, used for e.g. power cables and automotive bearings (Ciacci et al., 2015). While tellurium is used as a metallurgical additive to improve the machinability of the alloys, it may contribute to the characteristics of the metal product, such as the resistance to vibration and fatigue of lead alloys (Kavlak and Graedel, 2013a). The latter authors considered the metallurgical use of tellurium to be dissipative, and seemingly did not account for it as part of the in-use stocks. In this dataset, we consider such use of tellurium to be dissipation of type C, since tellurium remains in the metal product over its lifetime and is in theory recyclable from its alloys (Ciacci et al., 2015). Therefore, the metallurgical uses of tellurium are here aggregated in the alloys sector.</p> <p>Other uses of tellurium are diverse and include catalysts, chemicals, pigments, germicide and fungicide, lubricants, many of which are inherently dissipative (Ciacci et al., 2015; Kavlak and Graedel, 2013a). To reflect this, half of other uses are classified as other punctual applications and attributed a 100% dissipation rate, while the remainder share is classified in Other miscellaneous. The following end-use distribution is estimated to be representative of 2010-2019:</p> <table><tr><td>Alloys & solders</td><td>15%</td></tr><tr><td>Electronics</td><td>30%</td></tr><tr><td>Other industrial, military & energy applications</td><td>5%</td></tr><tr><td>Other punctual applications</td><td>5%</td></tr><tr><td>Rubber</td><td>5%</td></tr><tr><td>Solar cells</td><td>40%</td></tr></table> | Alloys & solders | 15% | Electronics | 30% | Other industrial, military & energy applications | 5% | Other punctual applications | 5% | Rubber | 5% | Solar cells | 40% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| Alloys & solders | 15% | | | | | | | | | | | | | |
| Electronics | 30% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 5% | | | | | | | | | | | | | |
| Other punctual applications | 5% | | | | | | | | | | | | | |
| Rubber | 5% | | | | | | | | | | | | | |
| Solar cells | 40% | | | | | | | | | | | | | |
| Production yield | 5% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | 62% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| New scrap recovery | 54% (Helbig et al., 2020, based on Kavlak and Graedel, 2013a) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |

| | | |
|-------------------------------|--|---|
| Remelting | 100% (Helbig et al., 2020, based on Kavлак and Graedel, 2013a) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | Tellurium used in other punctual applications is estimated to cover dissipative uses of tellurium as mentioned by Ciacci et al. (2015), and a dissipation in use rate of 100% is reported for that sector. Other uses are estimated not to be dissipated in use, although the metallurgical use of tellurium as well as its use in rubber are considered as dissipative uses of type C, highlighting that tellurium is currently unrecyclable from these applications (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Some tellurium may be recovered from thermoelectric devices and solar panels, especially from copper converters (Ciacci et al., 2015). Although this amount is considered negligible by some authors (European Commission, 2020c; Nassar et al., 2012), the BRGM report that the global EOL-RR of tellurium may range between 1 and 7% (BRGM, 2018g), citing the International Copper Study Group. Based on this information and considering a remelting yield of 100%, we report a collection yield of 5% for electronics and 1% for solar cells. | Per sector; please refer to Supplementary Data |

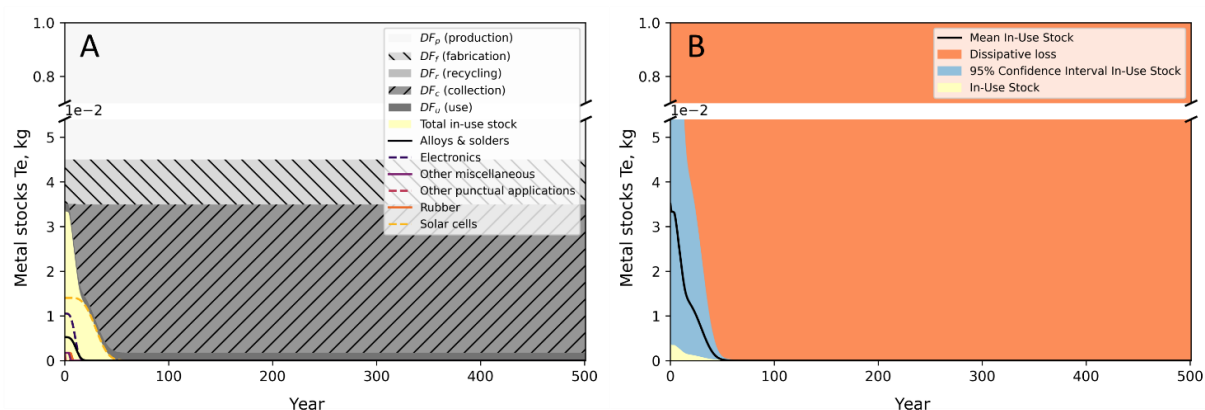


Figure B36. In-use stocks and losses of tellurium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.35 Barium**Table B44. Barium.**

| Barium | Ba, element number 56 | Uncertainty | | | | | | |
|--|--|--|-----|---------------------|-----|---------------|-----|---|
| End uses | <p>Barium is mostly used as part of barites used in drilling fluids for the oil and gas industry (European Commission, 2020a; Johnson et al., 2017). Recent reports indicate that between 69% and 90% of barium is used by for drilling fluids globally (Johnson et al., 2017; The Barytes Association, 2020). The variation may be explained by unpredictable changes in demand for barites linked to the oil and gas industry. An average of 80% is assumed to be representative of end-use of barium in drilling fluids based on UNEP (2011), which appear to be fairly constant with earlier data, e.g. 78% in 1993 (Albouy and Rousseau, 1993) and 84% in 2008/2009 (Panousi et al., 2016).</p> <p>Other uses include chemicals used for electronics, television screens, glass and ceramics, and medical applications (barium meals), as well as fillers used in the car, rubber and paint industries as well as various radiation shielding applications (The Barytes Association, 2020; USGS, 2020). Although it may be estimated that chemicals and fillers each represent about half of the remaining other uses (The Barytes Association, 2020), it is not possible to precisely disaggregate these in actual end-uses with the available information. Hence, 10% of barium end-uses are reported as other industrial applications, and 10% in other miscellaneous applications, to reflect its various potential end-use applications. The following distribution is estimated to be representative of recent years, i.e. 2015-2019:</p> <table><tr><td>Other industrial, military & energy applications</td><td>10%</td></tr><tr><td>Other miscellaneous</td><td>10%</td></tr><tr><td>Well drilling</td><td>80%</td></tr></table> | Other industrial, military & energy applications | 10% | Other miscellaneous | 10% | Well drilling | 80% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 2 |
| Other industrial, military & energy applications | 10% | | | | | | | |
| Other miscellaneous | 10% | | | | | | | |
| Well drilling | 80% | | | | | | | |
| Production yield | Panousi et al. (2016) provide an informed estimate of the mining yield of 80%. As barites are mostly used as a raw mineral in various applications (cement, drilling fluids, etc.), it is assumed that the additional processing of barites in other pure barium compounds represents a negligible share of production losses. | U1: 3 U2: 2 U3: 1 U4: 3 U5: 1 | | | | | | |
| Fabrication and manufacturing | It is estimated that small losses may incur from various processes along the fabrication and manufacturing chains, and a yield of 95% is assumed. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | |
| New scrap recovery | N/A; and 0% is reported | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Remelting | N/A; and 0% is reported | U1: 3 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Dissipation in use | Is some situations, drilling fluids may be considered to be recycled (or reused) to a certain extent (Johnson et al., 2017). Either way, most drilling fluids will end up as dissipated due to the way they are used | Per sector; please refer to | | | | | | |

| | | |
|-------------------------------|---|--|
| | directly in the environment. In this dataset, it is considered that such dissipation is covered in the EoL-RR of 0% reported for this application. Some medical applications (barium meals) may also be considered to be dissipative, although these were estimated to cover a negligible fraction of other uses reported above and were not considered in this dataset. | Supplementary Data |
| Collection and sorting | According to Johnson et al. (2017), barium is not readily recovered from applications other than drilling fluids (cf. dissipation in use box). The European Commission indicate that some barium used in glass may be considered to be functionally recycled, and indicate a recycling input rate of 1% for barites (European Commission, 2020a). Graedel et al. (2011) report a recycling rate below 1% for barium. We here assume the functional recycling of barium to be globally negligible, like Panousi et al. (2016). | Per sector; please refer to Supplementary Data |

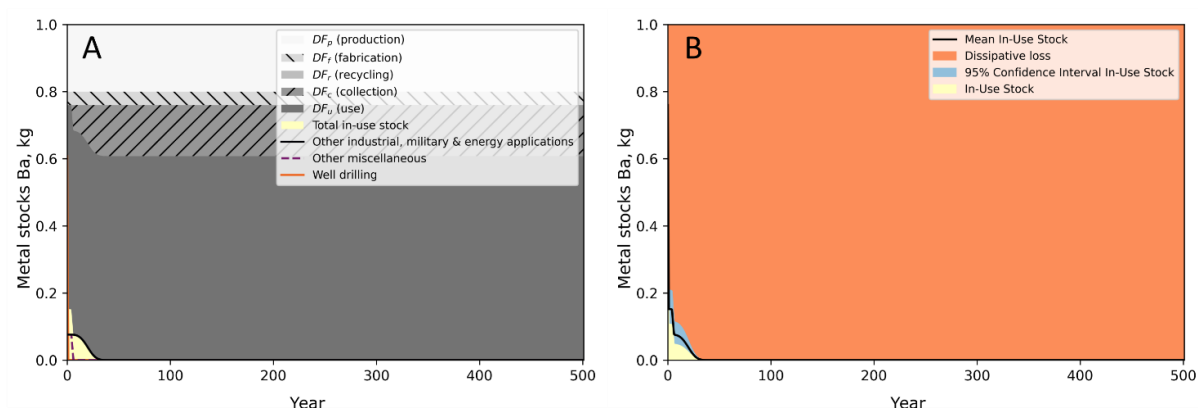


Figure B37. In-use stocks and losses of barium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.36 Lanthanum**Table B45. Lanthanum.**

| Lanthanum | La, element number 57 | Uncertainty | | | | | | | | | | | | | | | | | | |
|--|--|---|-----|--|----|------------------------------|-----|-------------|------|------------------|----|----------|----|--|----|-----------------------------|----|-----------|----|---|
| End uses | <p>The general method for REE distribution into end-use categories is described in section B.2.3.3.2. End-uses for 2010 reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from (Peiró et al., 2013). End-uses are then re-aggregated in order to fit within the harmonized end-use distributions of this dataset. For example, the 3.7% end-use of lanthanum as green phosphors is disaggregated into LCD screens, plasma panels and lighting applications; then, plasma panels and LCD screens are aggregated in the electronics category, and lighting applications in their designated category. The most important use of lanthanum is as FCCs. FCCs undergo particularly harsh reaction conditions and deactivate quickly, and hence need to be constantly regenerated with fresh catalysts (Vogt and Weckhuysen, 2015). The authors estimate that their lifetime is of about 1 month before they become deactivated. We aggregated FCCs into the chemicals category, for which a dissipation in use rate of 100% is reported. The use of lanthanum for glass polishing is comprised in the other punctual applications category. The following end-uses for lanthanum are estimated to be representative of the global end-uses of lanthanum in 2012:</p> <table><tr><td>Alloys & solders</td><td>10%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>9%</td></tr><tr><td>Batteries (electric vehicle)</td><td>17%</td></tr><tr><td>Electronics</td><td>0.4%</td></tr><tr><td>Glass & ceramics</td><td>6%</td></tr><tr><td>Lighting</td><td>1%</td></tr><tr><td>Other industrial, military & energy applications</td><td>9%</td></tr><tr><td>Other punctual applications</td><td>1%</td></tr><tr><td>Transport</td><td>1%</td></tr></table> | Alloys & solders | 10% | Batteries (consumer electronics & lead acid) | 9% | Batteries (electric vehicle) | 17% | Electronics | 0.4% | Glass & ceramics | 6% | Lighting | 1% | Other industrial, military & energy applications | 9% | Other punctual applications | 1% | Transport | 1% | U1: 2 U2: 3 U3: 1 U4: 2 U5: 2 |
| Alloys & solders | 10% | | | | | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 9% | | | | | | | | | | | | | | | | | | | |
| Batteries (electric vehicle) | 17% | | | | | | | | | | | | | | | | | | | |
| Electronics | 0.4% | | | | | | | | | | | | | | | | | | | |
| Glass & ceramics | 6% | | | | | | | | | | | | | | | | | | | |
| Lighting | 1% | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 9% | | | | | | | | | | | | | | | | | | | |
| Other punctual applications | 1% | | | | | | | | | | | | | | | | | | | |
| Transport | 1% | | | | | | | | | | | | | | | | | | | |
| Production yield | 60% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 | | | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 86% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 | | | | | | | | | | | | | | | | | | |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 | | | | | | | | | | | | | | | | | | |
| Remelting | 100% (assumption) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | | | | | |

| | | |
|-------------------------------|--|---|
| Dissipation in use | About 3% of lanthanum can be assumed to be lost to volatilization during glass polishing (Ciacci et al., 2015). We also note a dissipation in use rate of 2% considering the rate reported by Ciacci and colleagues for other elements used in autocatalysts (classified in the transport sector). Furthermore, given the rapid deactivation of FCCs, we approximate FCC losses with a dissipation in use rate of 100%. Dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 5% is reported for lanthanum used in batteries, 5% in lighting applications, and 0% for other applications. It is assumed that the one-year lifetime reported for glass polishing covers internal recycling of polishing powders, if ever it occurs. All of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data |

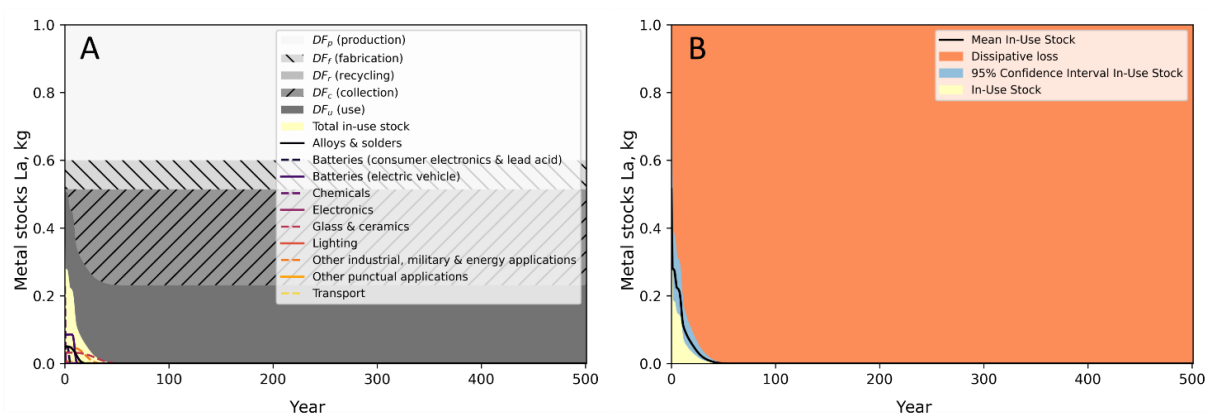


Figure B38. In-use stocks and losses of lanthanum over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.37 Cerium**Table B46. Cerium.**

| Cerium | Ce, element number 58 | Uncertainty |
|-------------------------------|--|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). Then, end-uses are re-aggregated in order to fit within the harmonized end-use distributions of this dataset. Alike lanthanum, FCCs are categorized as chemicals and modelled with a dissipation in use rate of 100% to approximate deactivation losses. Glass polishing is categorized under other punctual applications. The following end-uses for cerium are estimated to be representative of the global end-uses of cerium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 2 |
| | Alloys & solders | 19% |
| | Batteries (consumer electronics & lead acid) | 1% |
| | Batteries (electric vehicle) | 2% |
| | Chemicals | 5% |
| | Electronics | 1% |
| | Glass & ceramics | 13% |
| | Lighting | 3% |
| | Other industrial, military & energy applications | 8% |
| | Other punctual applications | 36% |
| | Transport | 13% |
| Production yield | 58% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 85% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | 100% (assumption) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | All of cerium chemicals, including FCCs, are assumed to be wholly dissipated in use. Moreover, about 3% of cerium can be assumed to be lost to volatilization during glass polishing, and 2% from the use in automotive catalytic converters, while dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 5% is reported for cerium used in batteries, 5% in lighting applications, and 0% for other applications. It is assumed that the one-year lifetime reported for glass polishing covers internal recycling of polishing powders, if ever it occurs. All of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data |

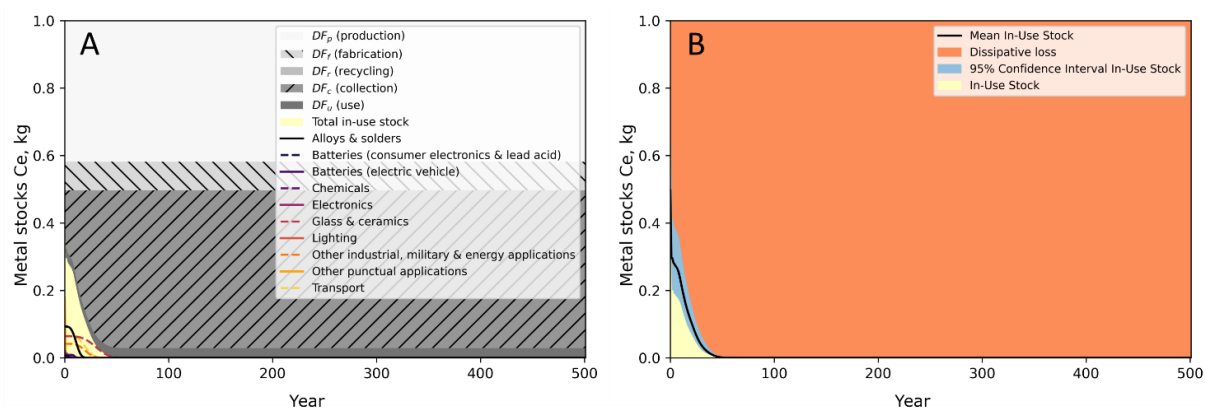


Figure B39. In-use stocks and losses of cerium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.38 Praseodymium**Table B47. Praseodymium.**

| Praseodymium | Pr, element number 59 | Uncertainty |
|-------------------------------|---|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. A small tweak to the general method was required to establish end-uses of praseodymium, since it was not reported to be used as phosphors in the works of Peiró et al. (2013). Jayachandiran and Kennedy (2020) report most common uses of praseodymium phosphors to be optical displays, pressure sensors, lighting, dosimetry and thermal sensors. Praseodymium can also replace a share of neodymium in Nd–Fe–B magnets, and is also used in laser crystals and pigments for glass and ceramics (Binnemans et al., 2018). Magnets are split between electronics, EVs (aggregated in the transport category) and large magnet applications (e.g., wind turbines). No quantified information could be found for praseodymium used in phosphors, and we assume an average distribution of praseodymium based on average REE use of 16% in electronic appliances (LCDs and plasma displays) and 84% in lighting applications, calculated from the data of Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of praseodymium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 3 |
| | Alloys & solders | 4% |
| | Batteries (consumer electronics & lead acid) | 1% |
| | Batteries (electric vehicle) | 3% |
| | Electronics | 54% |
| | Glass & ceramics | 7% |
| | Lighting | 9% |
| | Magnets (large) | 6% |
| | Other industrial, military & energy applications | 2% |
| | Other punctual applications | 2% |
| | Transport | 12% |
| | Production yield | 60% (cf. section B.2.3.3.1) |
| Fabrication and manufacturing | 68% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | 59% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 3 |
| Remelting | 100%; assumption, based on Du and Graedel (2011a). The remelting yield may be included in the new scrap recovery yield reported in the MFA of Du and Graedel. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | About 3% of praseodymium can be assumed to be lost to volatilization during glass polishing (Ciacci et al., 2015). While the authors mention that some dissipation may occur from the use of praseodymium in auto | Per sector; please refer to |

| | | |
|-------------------------------|---|--|
| | catalysts, praseodymium is not considered to be used in this application (the share of praseodymium included in transport sector represents its use in magnets for EV motors). Other dissipative losses from other applications are thought to be negligible (Ciacci et al., 2015). | Supplementary Data |
| Collection and sorting | 5% for battery applications, and 0% for other applications (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

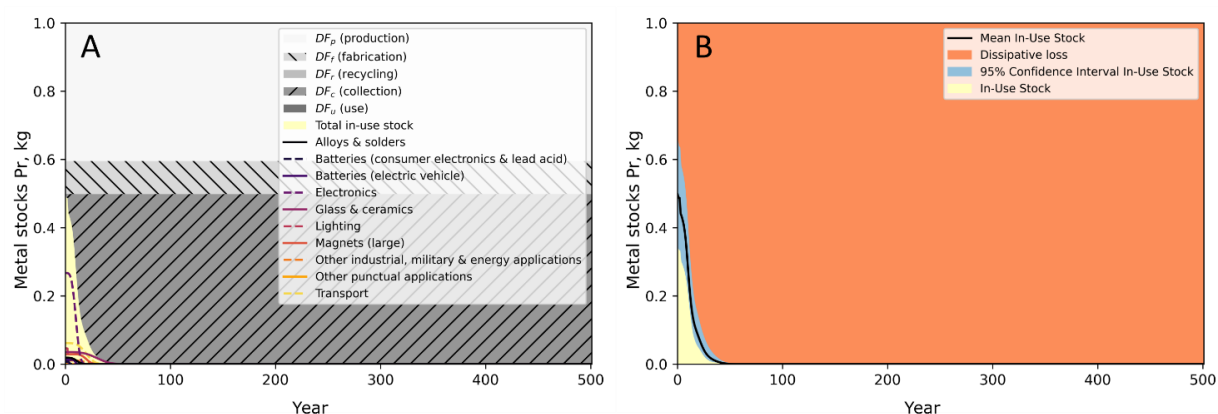


Figure B40. In-use stocks and losses of praseodymium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.39 Neodymium**Table B48. Neodymium.**

| Neodymium | Nd, element number 60 | Uncertainty |
|-------------------------------|---|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. The same tweak as for praseodymium is required to establish the end-use distribution of neodymium’s phosphors (cf. Table B48). The following distribution is estimated to be representative of the global end-uses of neodymium in 2012: | |
| | Alloys & solders | 2% |
| | Batteries (consumer electronics & lead acid) | 1% |
| | Batteries (electric vehicle) | 1% |
| | Electronics | 65% |
| | Glass & ceramics | 6% |
| | Lighting | 1% |
| | Magnets (large) | 7% |
| | Other industrial, military & energy applications | 0.4% |
| | Other punctual applications | 0.3% |
| | Transport | 17% |
| Production yield | 60% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 85% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 65% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | 100%; assumption, based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 2% of neodymium is estimated to be lost to corrosion over the lifetime of neodymium magnets (Ciacci et al., 2015). While the authors mention potential dissipation from the use of neodymium in auto catalytic converters, it was not considered to be used in this application in 2012 (the share of neodymium included in transport represents its use in magnets for EV motors). Dissipation in use from other applications are believed to be negligible (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | 5% for battery applications, and 0% for other applications (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

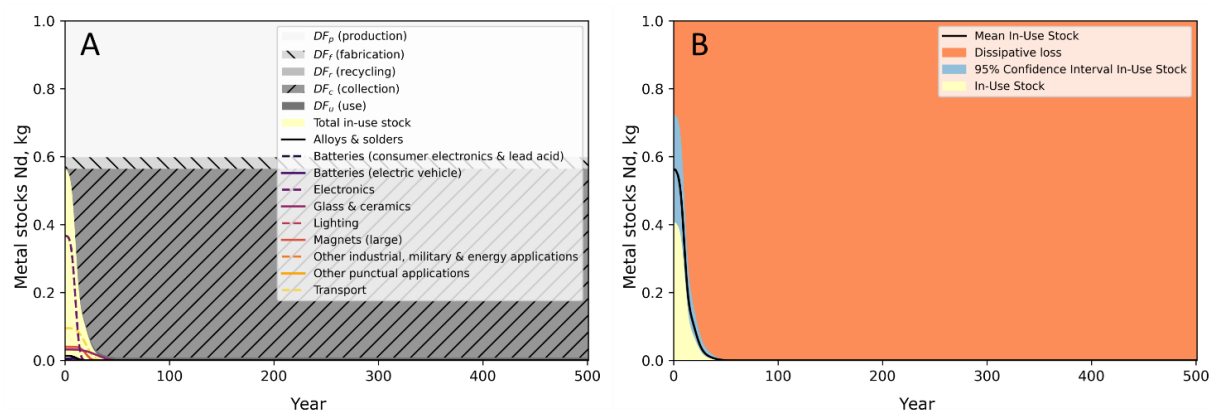


Figure B41. In-use stocks and losses of neodymium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.40 Samarium**Table B49. Samarium.**

| Samarium | Sm, element number 62 | Uncertainty |
|-------------------------------|---|---|
| End uses | While samarium was reported to be mostly used in NiMH batteries around 2008 (Graedel et al., 2013; Peiró et al., 2013), these had been mostly replaced by lithium-ion batteries by 2014, and samarium’s principal use became permanent samarium-cobalt magnets, representing about 97% of its uses (Bru et al., 2015; European Commission, 2020a). Considering the wide range of applications for such magnets, including e.g. aerospace, microwave communications, instrumentation, electrical engineering, and magnetic machinery (Yi, 2014), they are added to the other industrial sector rather than the large magnets category. Other samarium uses are added to the other miscellaneous category. The following end-uses are reported for samarium for the year 2012, and are estimated to have remained stable in recent years: | U1: 2 U2: 1 U3: 1 U4: 3 U5: 3 |
| | Other industrial, military & energy applications | 97% |
| | Other miscellaneous | 3% |
| Production yield | 63% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 86% (Du and Graedel, 2011a) | U1: 3 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | N/A, 0% reported in this dataset. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Dissipation in use | While some minor end-uses of samarium may be dissipative, we report a rate of 0% for all applications, based on Ciacci et al. (2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

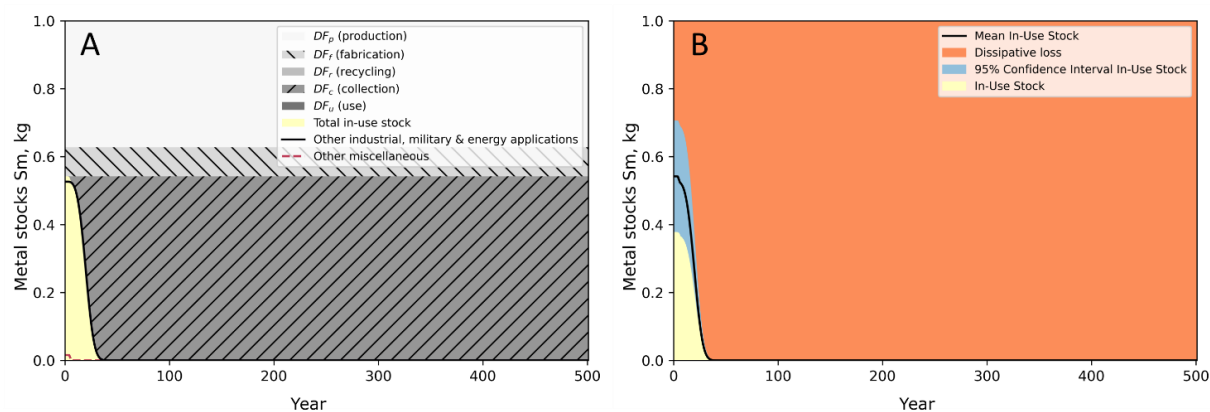


Figure B42. In-use stocks and losses of samarium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.41 Europium

Table B50. Europium.

| Europium | Eu, element number 63 | Uncertainty |
|-------------------------------|--|---|
| End uses | Few applications make use of europium aside from phosphors used in lamps (Binnemans et al., 2018). The general method for REE distribution into end-use categories is described in section B.2.3.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of europium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 2 |
| | Electronics | 17% |
| | Lighting | 80% |
| | Other industrial, military & energy applications | 4% |
| Production yield | 62% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 80%, with the assumption that both >0.1t losses reported for fabrication and manufacturing are equal to 0.03t each (Du and Graedel, 2011a) | U1: 3 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | 100% (assumption) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 10% is reported for europium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data |

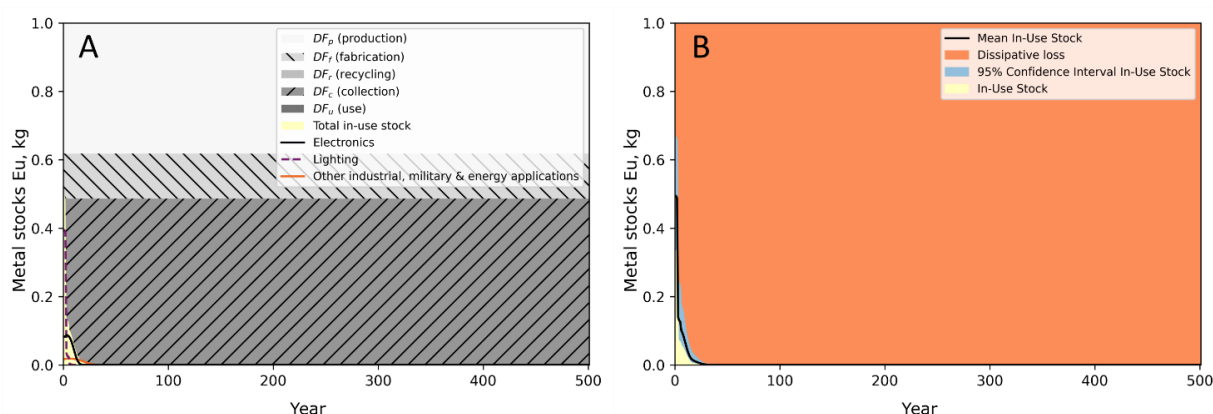


Figure B43. In-use stocks and losses of europium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.42 Gadolinium**Table B51. Gadolinium.**

| Gadolinium | Gd, element number 64 | Uncertainty |
|-------------------------------|--|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). Moreover, 10% out of the 14% reported as other uses are assumed to be a punctual use as a tracer in medical imaging (Binnemans et al., 2018; Ciacci et al., 2015). The following distribution is estimated to be representative of the global end-uses of gadolinium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 3 |
| | Alloys & solders | 28% |
| | Electronics | 4% |
| | Lighting | 19% |
| | Magnets (large) | 35% |
| | Other industrial, military & energy applications | 4% |
| | Other punctual applications | 10% |
| Production yield | 64% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 70% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | 20% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 3 |
| Remelting | 100%; assumption based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | The dissipation in use from contrasting agents for MRI could be considered to be of type B or C, depending on if it is considered to be lost once discarded with wastewater. Ciacci et al. (2015) assumed that roughly 20% is dissipated during use (dissipation in use of type B), while the remainder share is currently unrecyclable (dissipation in use of type C). These same values are reported in the dataset, and dissipation in use rates of 0% are reported for other applications (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 5% is reported for gadolinium used in lighting applications, and 0% for other applications. In order to avoid a conflictual remelting rate with that considered for new scrap recovery, all of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data |

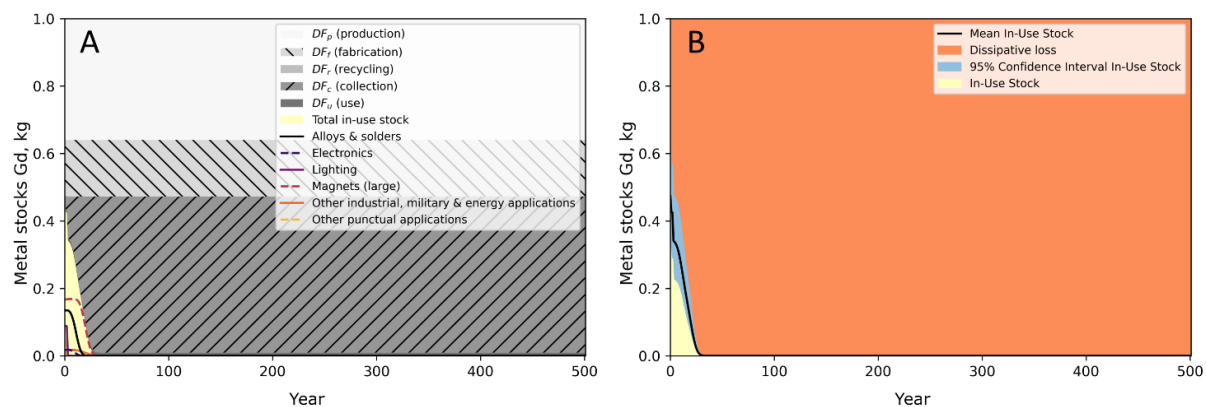


Figure B44. In-use stocks and losses of gadolinium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.43 Terbium**Table B52. Terbium.**

| Terbium | Tb, element number 65 | Uncertainty |
|-------------------------------|--|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of terbium in 2012: | |
| | Electronics | 18% |
| | Lighting | 53% |
| | Magnets (large) | 7% |
| | Other industrial, military & energy applications | 5% |
| | Transport | 16% |
| Production yield | 65% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 80%, with the assumption that both >0.1t losses reported for fabrication and manufacturing are equal to 0.03t each (Du and Graedel, 2011a) | U1: 3 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 0% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | 100% (assumption) | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | Based on section B.2.3.3.5, an EOL-RR of 10% is reported for terbium used in lighting applications, and 0% for other applications. All of the losses due to waste management and recycling are reported as collection losses. | Per sector; please refer to Supplementary Data |

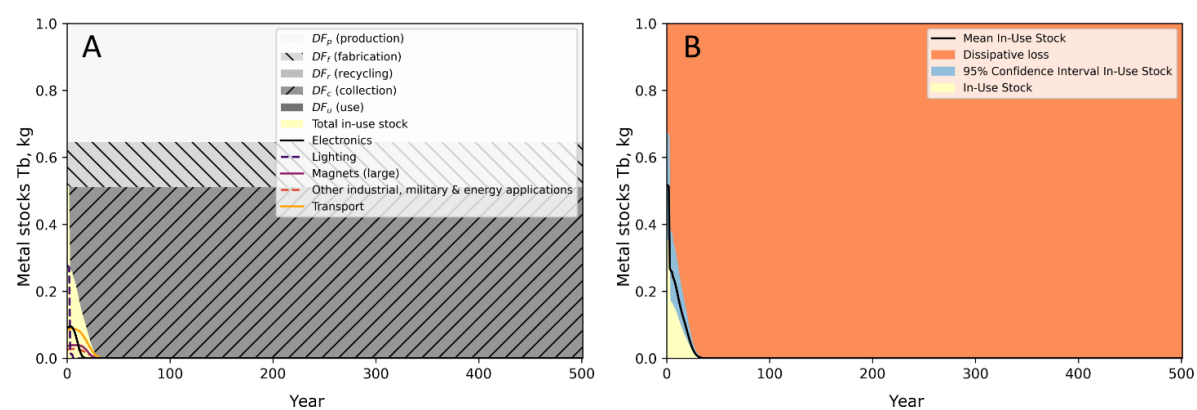
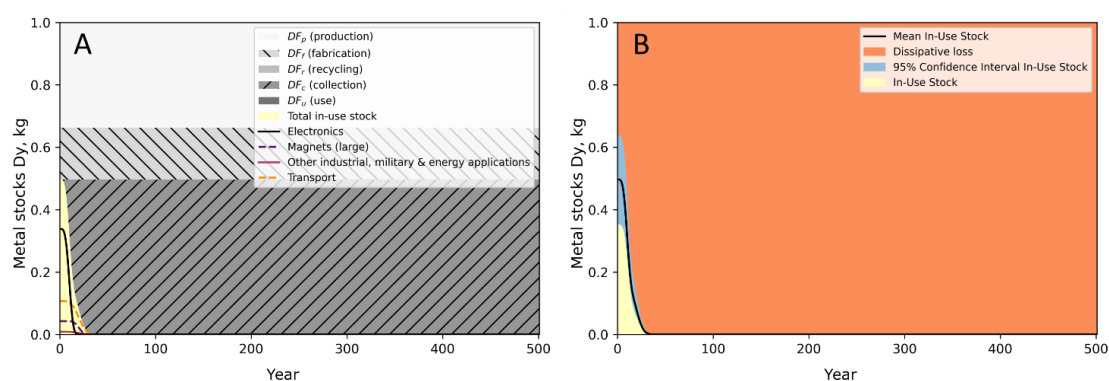


Figure B45. In-use stocks and losses of terbium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.44 Dysprosium**Table B53. Dysprosium.**

| Dysprosium | Dy, element number 66 | Uncertainty |
|-------------------------------|---|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. Dysprosium is nearly exclusively used in permanent neodymium magnets (BRGM, 2016a). End-uses reported in the 2014 European criticality report (European Commission, 2014) are matched and disaggregated with end-use data from Peiró et al. (2013). The following distribution is estimated to be representative of the global end-uses of dysprosium in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 2 |
| | Electronics | 68% |
| | Magnets (large) | 9% |
| | Other industrial, military & energy applications | 2% |
| | Transport | 22% |
| | | |
| Production yield | 66% (cf. section B.2.3.3.1) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | 56% (Du and Graedel, 2011a) | U1: 1 U2: 3 U3: 1 U4: 3 U5: 2 |
| New scrap recovery | 57% (Du and Graedel, 2011a) | U1: 3 U2: 3 U3: 1 U4: 3 U5: 2 |
| Remelting | 100%; assumption, based on Du and Graedel (2011a). The yield of remelting may be included in the new scrap recovery yield reported in the MFA of the authors. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

**Figure B46. In-use stocks and losses of dysprosium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.**

B.3.2.45 Holmium**Table B54. Holmium.**

| Holmium | Ho, element number 67 | Uncertainty | | | | | | |
|--|--|---|-----|-----------------|-----|--|-----|---|
| End uses | <p>It is difficult to define holmium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No global end-use distribution specific of holmium could be found. The BRGM lists four main potential applications for holmium: YAG lasers, the coloration of glass products, metal halide lamps and strong magnets used e.g. in magnetic flux concentrators (Bru et al., 2015). Holmium is thought to be used mostly for such magnets in the US (Graedel et al., 2013), while glass products are thought to be the only use for holmium in Europe (European Commission, 2020a; Guyonnet et al., 2015). Without further information, we assume a distribution of 1/3 each in magnets, glass products, and other industrial, military & energy applications. The following distribution is estimated to be representative of holmium end-uses in recent years:</p> <table><tr><td>Glass & ceramics</td><td>33%</td></tr><tr><td>Magnets (large)</td><td>33%</td></tr><tr><td>Other industrial, military & energy applications</td><td>33%</td></tr></table> | Glass & ceramics | 33% | Magnets (large) | 33% | Other industrial, military & energy applications | 33% | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Glass & ceramics | 33% | | | | | | | |
| Magnets (large) | 33% | | | | | | | |
| Other industrial, military & energy applications | 33% | | | | | | | |
| Production yield | 67% (cf. section B.2.3.3.1) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 | | | | | | |
| Fabrication and manufacturing | An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 | | | | | | |
| New scrap recovery | No recovery of new scraps is expected to occur (European Commission, 2020a). | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Remelting | N/A, 0% reported in this dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Dissipation in use | The use in magnets is not considered to be dissipated in use (Ciacci et al., 2015). Based on dissipation reported for other REEs, the other main uses for holmium are unlikely to be dissipative and are also reported as 0%. | Per sector; please refer to Supplementary Data | | | | | | |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data | | | | | | |

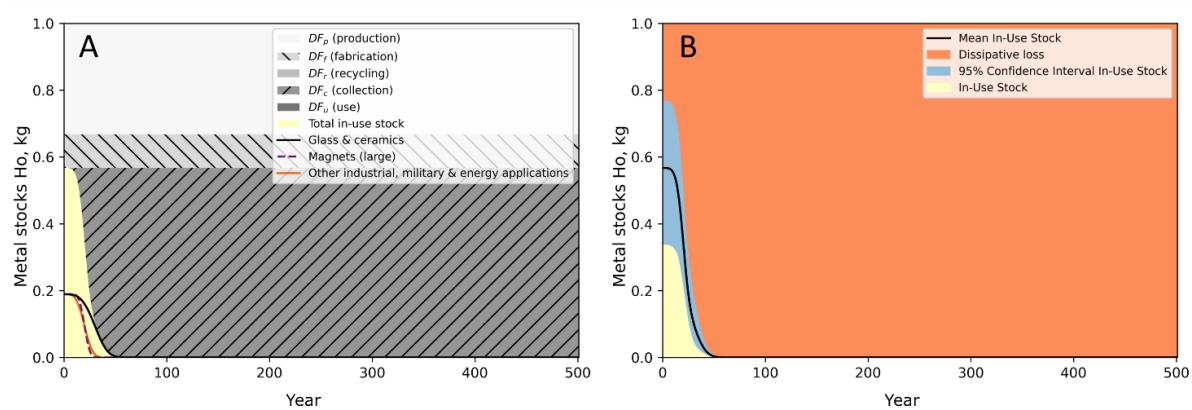


Figure B47. In-use stocks and losses of holmium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.46 Erbium**Table B55. Erbium.**

| Erbium | Er, element number 68 | Uncertainty |
|-------------------------------|--|---|
| End uses | The general method for REE distribution into end-use categories is described in section B.2.3.3.2. In 2012, about 72% of erbium was used as a pink colorant in glass products and in EDFA amplifiers for optical communication, 25% as a dopant in phosphors, and 3% in various uses such as YAG lasers, alloys (especially for the machining of vanadium alloys) and nuclear reactor control rods (Bru et al., 2015; European Commission, 2014). Without specific quantifications of the share of erbium used for optical communications, and considering that the telecommunication sector is attributed the same average lifetime of 30 years as the glass & ceramics sector, both end-uses are aggregated altogether in the glass category. The following distribution is estimated to be representative of erbium end-uses in 2012: | U1: 2 U2: 3 U3: 1 U4: 2 U5: 3 |
| | Electronics | 25% |
| | Glass & ceramics | 72% |
| | Other industrial, military & energy applications | 3% |
| Production yield | 67% (cf. section B.2.3.3.1) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. The yield is assumed to account for new scrap recycling if ever it occurs. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | N/A, 0% reported in this dataset. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Remelting | N/A, 0% reported in this dataset. | U1: 3 U2: 1 U3: 1 U4: 3 U5: 3 |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

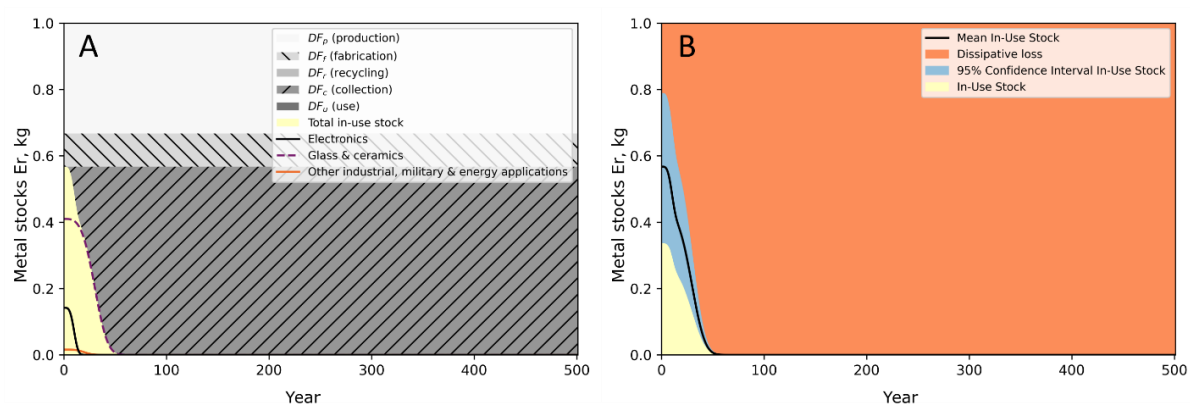


Figure B48. In-use stocks and losses of erbium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.47 Thulium**Table B56. Thulium.**

| Thulium | Tm, element number 69 | Uncertainty | | | | |
|--|---|---|-----|-----------------------------|-----|---|
| End uses | <p>It is difficult to define thulium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No precise global end-use distribution specific of thulium could be found. Thulium may be used as a dopant in fiber lasers and phosphors, in magnetic ceramics, as a fluorescent agent in anti-fraud Euro banknotes, and in portable x-ray devices (Bru et al., 2015). It is estimated that 45% of thulium is used as a radiation source (e.g., in portable x-ray devices) (Ciacci et al., 2015). Given the variety of uses and lack of precise distribution, the remaining 55% is classified in other industrial, military & energy applications. The following distribution is assumed to be representative of thulium end-uses in recent years:</p> <table><tr><td>Other industrial, military & energy applications</td><td>55%</td></tr><tr><td>Other punctual applications</td><td>45%</td></tr></table> | Other industrial, military & energy applications | 55% | Other punctual applications | 45% | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Other industrial, military & energy applications | 55% | | | | | |
| Other punctual applications | 45% | | | | | |
| Production yield | 67% (cf. section B.2.3.3.1) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 | | | | |
| Fabrication and manufacturing | An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 | | | | |
| New scrap recovery | No recovery of new scraps is expected to occur (European Commission, 2020a). | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | |
| Remelting | N/A, 0% reported in this dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | |
| Dissipation in use | 100% for thulium used as a radiation source in punctual applications, and 0% for other uses (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data | | | | |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data | | | | |

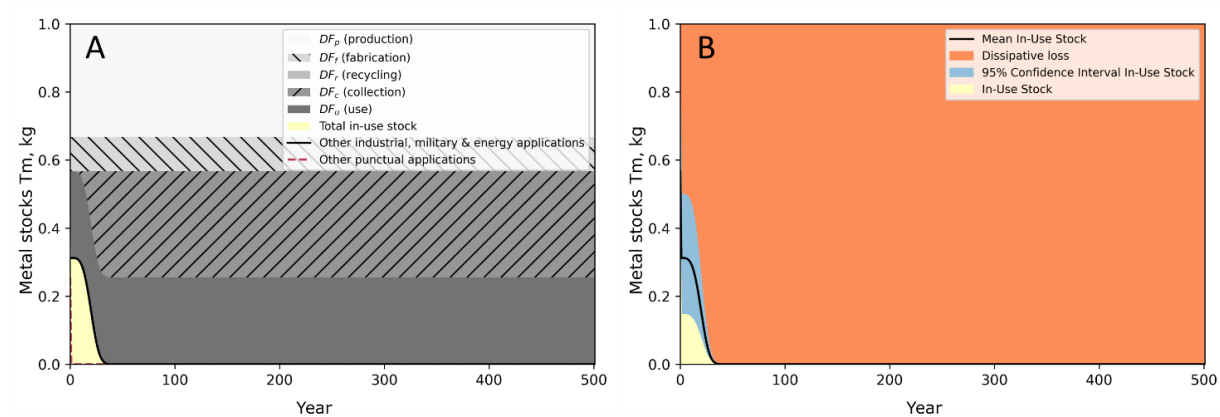


Figure B49. In-use stocks and losses of thulium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.48 Ytterbium**Table B57. Ytterbium.**

| Ytterbium | Yb, element number 70 | Uncertainty |
|-------------------------------|--|---|
| End uses | It is difficult to define ytterbium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). Ytterbium may be used in a variety of applications such as glass-optical devices including YAG lasers, portable x-ray devices and stress gauges for seismic measurements (Bru et al., 2015; Ciacci et al., 2015; European Commission, 2020a). Alike thulium, it is estimated that 45% of ytterbium is used as a radiation source (e.g., in portable x-ray devices) based on (Ciacci et al., 2015), which is classified in other punctual applications. The remaining share is reported as other industrial, military & energy applications. The following distribution is assumed to be representative of ytterbium end-uses in recent years: | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| | Other industrial, military & energy applications | 55% |
| | Other punctual applications | 45% |
| Production yield | 67% (cf. section B.2.3.3.1) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. The yield is assumed to account for new scrap recycling if ever it occurs. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | N/A, 0% reported in this dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | N/A, 0% reported in this dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 100% for ytterbium used as a radiation source (classified in other punctual applications), and 0% for other uses (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

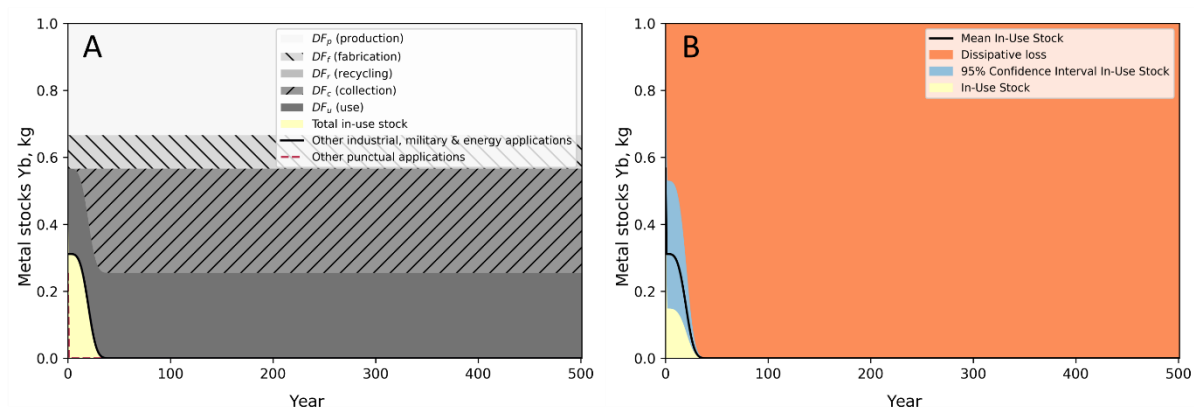


Figure B50. In-use stocks and losses of ytterbium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.49 Lutetium**Table B58. Lutetium.**

| Lutetium | Lu, element number 71 | Uncertainty |
|-------------------------------|---|---|
| End uses | It is difficult to define lutetium end-uses since they are used in niche applications and in small quantities (European Commission, 2020a, 2014). No global end-use distribution specific of lutetium could be found. It is believed to be used mostly in positron emission tomography, and to a lesser extent in nuclear medicine, specialty optics products and as catalysts for e.g. petroleum cracking and refining (Bru et al., 2015; Ciacci et al., 2015). It is estimated that 45% of lutetium undergoes inherently dissipative uses, based on Ciacci et al. (2015); the remaining shared is assumed to be split equally between glass products, catalysts and other industrial, military & energy applications . The following distribution is assumed to be representative of ytterbium end-uses in recent years, i.e. around 2010-2019: | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| | Catalysts (homogenous & aggressive env.) | 18% |
| | Glass & ceramics | 18% |
| | Other industrial, military & energy applications | 18% |
| | Other punctual applications | 45% |
| Production yield | 67% (cf. section B.2.3.3.1) | U1: 4 U2: 1 U3: 1 U4: 3 U5: 3 |
| Fabrication and manufacturing | An assumption of 85% fabrication and manufacturing yield is reported for Ho, Er, Tm, Yb and Lu, based on the process yields for other REEs. | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 |
| New scrap recovery | No recovery of new scraps is expected to occur (European Commission, 2020a). | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | N/A, 0% reported in this dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 100% for lutetium used as a radiation source in punctual applications, and 0% for other uses (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | 0% (cf. section B.2.3.3.5) | Per sector; please refer to Supplementary Data |

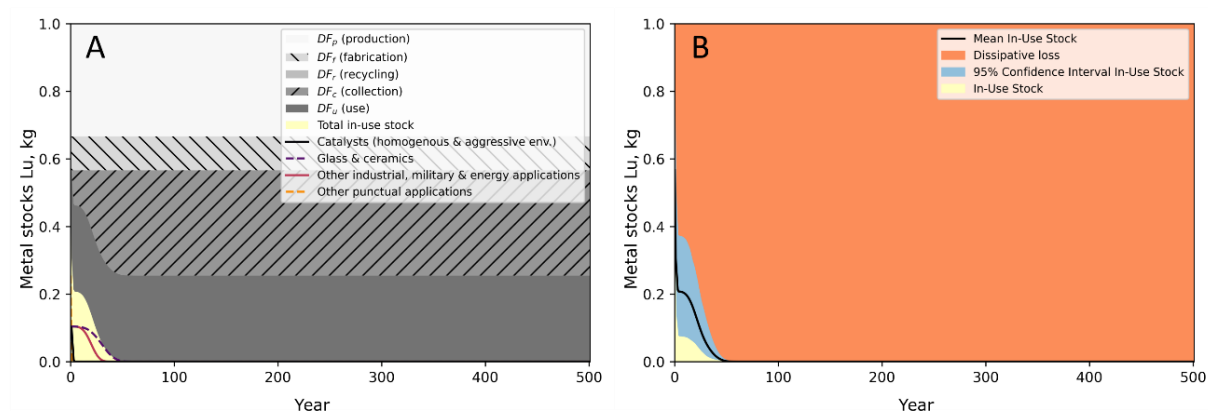


Figure B51. In-use stocks and losses of lutetium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.50 Hafnium**Table B59. Hafnium.**

| Hafnium | Hf, element number 72 | Uncertainty | | | | | | | | | | | | |
|--|--|---|-----|--|----|---------------|-----|-------------|----|----------------|-----|--|-----|---|
| End uses | <p>The end-uses distribution for hafnium are reported for years 2008 (Graedel et al., 2013), 2010-2014 (BRGM, 2018a) and 2016 (European Commission, 2020a). The main use of hafnium is in superalloys used in aerospace and nuclear fuel reprocessing plants (Graedel et al., 2013). The most recent distribution for 2016 is disaggregated with other available data. It is estimated that 45% out of 61% end-use of hafnium in superalloys is for aerospace, and the remaining 16% is used in reprocessing plants. End-uses in processing plants are categorized as infrastructure, and plasma cutting tips as cutting tools. Furthermore, the end-use as catalyst precursor is categorized in catalysts, and semi-conductors as well as optical applications, in electronics. The following distribution is considered to be representative of the year 2016:</p> <table><tr><td>Aviation</td><td>45%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>7%</td></tr><tr><td>Cutting tools</td><td>15%</td></tr><tr><td>Electronics</td><td>6%</td></tr><tr><td>Infrastructure</td><td>16%</td></tr><tr><td>Other industrial, military & energy applications</td><td>11%</td></tr></table> | Aviation | 45% | Catalysts (homogenous & aggressive env.) | 7% | Cutting tools | 15% | Electronics | 6% | Infrastructure | 16% | Other industrial, military & energy applications | 11% | U1: 3 U2: 2 U3: 1 U4: 2 U5: 1 |
| Aviation | 45% | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 7% | | | | | | | | | | | | | |
| Cutting tools | 15% | | | | | | | | | | | | | |
| Electronics | 6% | | | | | | | | | | | | | |
| Infrastructure | 16% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 11% | | | | | | | | | | | | | |
| Production yield | <p>Hafnium naturally occurs in zirconium minerals (zircon and baddeleyite) (BRGM, 2018a). It is produced exclusively as by-product of zirconium metal, i.e. from residues of zirconium tetrachloride purification. Hafnium production is “nearly forced” because zirconium used for nuclear fuel rod cladding must be free of hafnium (BRGM, 2018a). The main producers of hafnium are France, the US, China and Ukraine, which all have an important nuclear power sector (BRGM, 2018a).</p> <p>We estimate the production yield of hafnium by comparing its reported yearly production with the theoretical quantity that is extracted along with zircon. There is a 50:1 Zr to Hf ratio in zircon minerals, and a ratio of about 73:1 Zr to Hf ratio in baddeleyite (BRGM, 2018a; Jones et al., 2017). As most of the production originates from zircon, we consider an average ratio of 50:1 Zr to Hf ratio in the extracted ores. For the production of 1.38 million tons of zirconium concentrate in 2016, about 75 tons of hafnium was produced (BRGM, 2018a). Considering that a theoretical 28 000 tons of hafnium was extracted with zirconium concentrates (50:1 Zr to Hf ratio), a production yield of 0.27% can be calculated.</p> <p>It is reported that hafnium may also have accumulated in the tailings of primary igneous deposits from which zircon and hafnium have not been historically targeted (Jones et al., 2017). These are not included in this calculation.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | 95%, including the recovery of new scraps (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |

| | | |
|-------------------------------|--|---|
| New scrap recovery | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Dissipation in use | 0% (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data |
| Collection and sorting | No EOL recycling of hafnium occurs (BRGM, 2018a; Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |

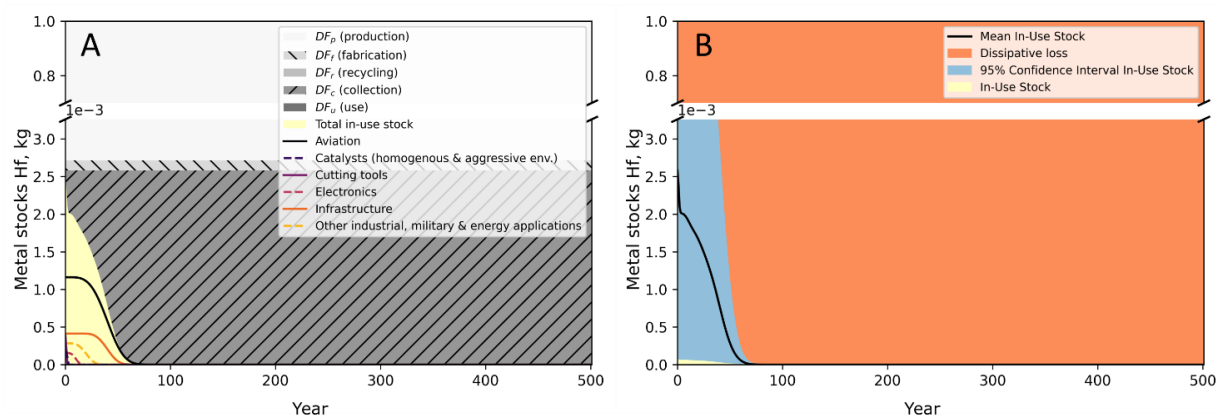


Figure B52. In-use stocks and losses of hafnium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.51 Tantalum**Table B60. Tantalum.**

| Tantalum | Ta, element number 73 | Uncertainty | | | | | | | | |
|--|--|--|-----|---------------|----|-------------|-----|--|-----|---|
| End-uses | <p>Global end-use distributions are available for 2008 (Graedel et al., 2015), 1975-2015 (Nassar, 2017) and 2018 (BRGM, 2020d). The most important end-use for tantalum is in capacitors, with 48% and 34% of the share of global end-uses in 2008 and 2018, respectively. Other uses include superalloys, chemicals, sputtering targets and cutting tools (BRGM, 2020d). The latest distribution of 2018 is reported in this dataset. It is not possible to further disaggregate metallurgical uses and chemicals uses with the available information, and both are classified as other industrial, military & energy applications given the variety of potential end-uses for both of these (e.g., heat exchangers, crucibles, prosthesis, and military applications for mill products; galvanizing, anodes and ceramics for tantalum chemicals) (Nassar, 2017). Tantalum used as a sputter target is used mostly for electronic devices such as magnetic storage media, inkjet printer heads, electronic circuitry and flat panel displays (European Commission, 2020a; Nassar, 2017), and are therefore aggregated in the electronics sector, along with capacitors. The following distribution is representative of the year 2018:</p> <table><tr><td>Alloys & solders</td><td>18%</td></tr><tr><td>Cutting tools</td><td>5%</td></tr><tr><td>Electronics</td><td>48%</td></tr><tr><td>Other industrial, military & energy applications</td><td>29%</td></tr></table> | Alloys & solders | 18% | Cutting tools | 5% | Electronics | 48% | Other industrial, military & energy applications | 29% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 2 |
| Alloys & solders | 18% | | | | | | | | | |
| Cutting tools | 5% | | | | | | | | | |
| Electronics | 48% | | | | | | | | | |
| Other industrial, military & energy applications | 29% | | | | | | | | | |
| Production yield | 65% (Helbig et al., 2020, based on Nassar, 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Fabrication and manufacturing | 76% (Helbig et al., 2020, based on Nassar, 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| New scrap recovery | 54% (Helbig et al., 2020, based on Nassar, 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Remelting | 100% (Helbig et al., 2020, based on Nassar, 2017) | U1: 1 U2: 2 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Dissipation in use | 1.6% for cutting tools (Nassar, 2017), 0% for other applications (Ciacci et al., 2015; Nassar, 2017) | Per sector; please refer to Supplementary Data | | | | | | | | |
| Collection and sorting | Helbig et al. (2020) calculated a collection yield of 21% based on Nassar (2017). The EOL-RR of tantalum results mainly from the recycling of carbides used for cutting tools, mill products and superalloys, while small amounts may also be recovered from capacitors (Nassar, 2017). Collection yields of 70 to 90%, 60% and 50% are reported for superalloys, mill products and carbides (Graedel et al., 2015; Nassar, 2017). Other applications are not considered to be functionally recycled. The collection | Per sector; please refer to Supplementary Data | | | | | | | | |

yield for the other category is calculated to be 19% based on the share of mill products in that category. Moreover, the EOL-RR of capacitors is estimated to be below 0.5% and considered to be negligible. The reported collection yields are the following: alloys, 80%; electronics, 0%; cutting tools, 50%; and other industrial applications, 19%.

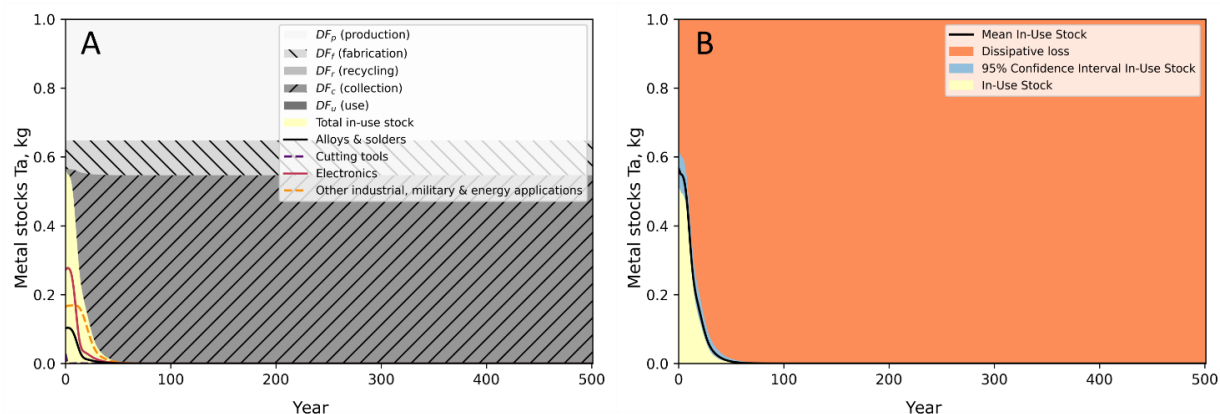


Figure B53. In-use stocks and losses of tantalum over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.52 Tungsten**Table B61. Tungsten.**

| Tungsten | W, element number 74 | Uncertainty | | | | | | | | | | | | |
|--|--|---|-----|--|----|---------------|-----|-------------|----|----------|----|---------------------|-----|---|
| End-uses | <p>Multiple global end-use distribution of tungsten are available, albeit generally including only first use sectors. Some recent distributions include 2008 (Graedel et al., 2015), some year between 2010 and 2012 (Ciacci et al., 2015), 2012-2016 (European Commission, 2020a), 2015 (BRGM, 2017j) and 2016 (ITIA, 2018). The most important use of tungsten in the studied years remained cemented carbides, with over 50% of its end uses. Other important uses include steel alloys, tungsten metal used in lighting, electronics and ammunition, as well as a range of other uses (e.g., catalysts, chemicals). The end-use distribution of 2015 (BRGM, 2017j) is considered. It is refined with other information available in the cited literature in order to provide a more disaggregated distribution of tungsten uses.</p> <p>Notably, the 7% reported as others is considered to be used as chemicals (3%), and 2% each in catalysts and superalloys, based on Ciacci et al. (2015). Chemicals are classified as others (short lived) based on their suggested applications (pigments, absorbent gels). Superalloys are aggregated within alloys along with steel. The 17% share of tungsten metal is assumed to be split between mill products (8%), lighting (2%) and electronics (7%) (Ciacci et al., 2015; Graedel et al., 2015). Mill products are aggregated in the Other miscellaneous category based on the expected average lifetime for these products (Graedel et al., 2015). The alloys category includes steels and alloys used in a range of applications including wear and high speed steel applications, construction tools, energy and aeronautics applications (BRGM, 2017j; European Commission, 2020a). The following distribution is estimated to be representative of the year 2015:</p> <table><tr><td>Alloys & solders</td><td>23%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>2%</td></tr><tr><td>Cutting tools</td><td>55%</td></tr><tr><td>Electronics</td><td>7%</td></tr><tr><td>Lighting</td><td>2%</td></tr><tr><td>Other miscellaneous</td><td>11%</td></tr></table> | Alloys & solders | 23% | Catalysts (homogenous & aggressive env.) | 2% | Cutting tools | 55% | Electronics | 7% | Lighting | 2% | Other miscellaneous | 11% | U1: 2 U2: 2 U3: 1 U4: 1 U5: 1 |
| Alloys & solders | 23% | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 2% | | | | | | | | | | | | | |
| Cutting tools | 55% | | | | | | | | | | | | | |
| Electronics | 7% | | | | | | | | | | | | | |
| Lighting | 2% | | | | | | | | | | | | | |
| Other miscellaneous | 11% | | | | | | | | | | | | | |
| Production yield | 89% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | 90% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| New scrap recovery | 100% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |

| | | |
|-------------------------------|--|---|
| Remelting | 100% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 |
| Dissipation in use | Some dissipation may occur from the use of tungsten in carbide cutting tools and catalysts. The dissipation rates are estimated to be 5% for the former, and 2% for the latter (Ciacci et al., 2015). Other applications are considered not to be dissipated during use (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>Helbig et al. (2020) calculated an overall collection rate of 32%, based on Meylan et al. (2015). This yield suggests that the EoL-RR of tungsten is in the higher bound of the EoL-RR range of 10 and 25% (BRGM, 2017j; UNEP, 2011). The latest EoL-RR per application proposed by Graedel et al. (2015) are considered for this dataset (year 2008) along with estimates reported by the International Tungsten Industry Association (ITIA, 2018). A remelting rate of 100% is taken into account.</p> <p>The yield for carbides is weighted based on the distribution of cutting tools, dies, and mining and construction tools included in that category. Estimated shares of 40%, 20% and 40% of cemented carbides are attributed for each of these applications based on the consulted literature. The resulting collection rate is of 41% for cemented carbides, slightly below the global estimate of 46% reported by ITIA (2018). This may be explicable by the inclusion of new scrap in the latter recycling rate.</p> <p>Similarly, the collection yield for alloys can be calculated by weighting the share of superalloys (2%) and steel products (21%) aggregated in that category, for which recycling rates of 80% and 50% are reported by Graedel et al. (2015), respectively. The resulting collection yield for the alloys category is of 52%. However, the ITIA estimates much lower recycling yields for tungsten contained in steel and alloys, with only around 15%. This is due to the low recycling rate of stellite steel parts (stellites) and of low-tungsten containing steels which may be mostly downcycled in ordinary steel (ITIA, 2018). Nonetheless, the ITIA acknowledges that the recycling rate of superalloys may be quite high. Based on this information, a collection yield of 15% is reported for the alloys category, instead of 52% suggested by (Graedel et al., 2015). Moreover, an EoL-RR of 0% for mill products is reported by Graedel et al. (2015), while the ITIA estimates a recycling rate of 22%, albeit acknowledging this rate to include a majority of powder metallurgical new scraps (ITIA, 2018). Without further information, we assume that the EoL-RR of tungsten for these applications is close to 0%, and a collection yield of 0% is reported. Based on these same two data sources, the collection yields for other applications are estimated to be negligible, and collection yields of 0% are reported.</p> | Per sector; please refer to Supplementary Data |

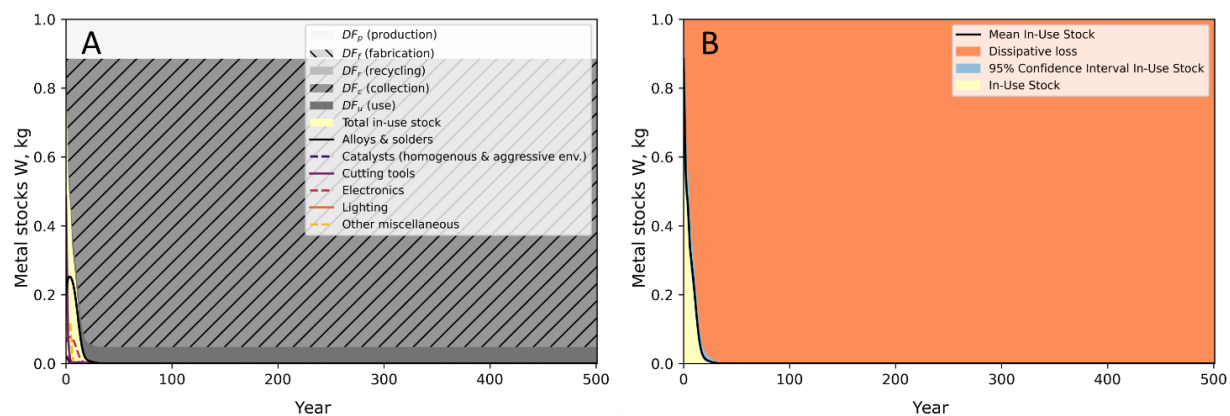


Figure B54. In-use stocks and losses of tungsten over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.53 Rhenium**Table B62. Rhenium.**

| Rhenium | Re, element number 75 | Uncertainty | | | | | | | | |
|--|--|---|-----|---|----|--|----|--|----|---|
| End-uses | <p>Rhenium is mostly used in superalloys used in the manufacture of gas turbine engines for e.g. aircrafts and energy production (BRGM, 2020e; European Commission, 2020c). Its other important use is as a catalysts used by the petroleum and petrochemistry industries (BRGM, 2020e; Ciacci et al., 2015). Other uses are various and include e.g. electric furnace resistances, filaments of incandescent lamps and anodes for X-ray tubes used in medical radiography (BRGM, 2020e). Global end-use distributions are available for 2008 (Ciacci et al., 2015; Graedel et al., 2015) and 2018 (BRGM, 2020e). The latter is based on USGS Mineral Commodity Summaries of 2019 and is considered to establish the end-use distribution for rhenium. Catalysts are split half and half between short and long lived catalysts to reflect the average lifetime of 5 years reported by Graedel et al. (2015). This is consistent with the lifetime considered for platinum-rhenium catalysts used in the petroleum industry (cf. Table B65). The following distribution is estimated to be representative of 2018:</p> <table><tr><td>Alloys & solders</td><td>80%</td></tr><tr><td>Catalysts (heterogeneous & stable env.)</td><td>8%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>8%</td></tr><tr><td>Other industrial, military & energy applications</td><td>5%</td></tr></table> | Alloys & solders | 80% | Catalysts (heterogeneous & stable env.) | 8% | Catalysts (homogenous & aggressive env.) | 8% | Other industrial, military & energy applications | 5% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 2 |
| Alloys & solders | 80% | | | | | | | | | |
| Catalysts (heterogeneous & stable env.) | 8% | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 8% | | | | | | | | | |
| Other industrial, military & energy applications | 5% | | | | | | | | | |
| Production yield | 50% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Fabrication and manufacturing | 100% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| New scrap recovery | 100% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Remelting | 100% (Helbig et al., 2020, based on Meylan et al., 2015) | U1: 1 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | |
| Dissipation in use | About 2% of the rhenium content of catalysts is estimated to be dissipated during use, while it is not dissipated in use in other applications (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data | | | | | | | | |

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| Collection and sorting | <p>Helbig et al. (2020) calculated a global collection yield of 56% based on Meylan et al. (2015). This rate is in line with the EoL-RR estimated by UNEP (2011). It is slightly higher than that suggest by the BRGM, which estimated the global recycling rate to be between 35 and 40% (BRGM, 2020e). This is explicable by the shutdown of the hydrometallurgical production of secondary rhenium in three recycling plants between 2014 and 2020 (BRGM, 2020e), resulting in a reduced recycling potential for superalloys. Unlike superalloys, the recycling of catalysts is supported by the high value of platinum along which rhenium is recycled.</p> <p>In this dataset, we estimate the collection yields taking into account the remelting yield of 100%. The closed-loop recycling rate of catalysts is estimated to be of about 80% (European Commission, 2020c). This yield is slightly lower than the 90% estimate reported in Graedel et al. (2015), and matches the approximated 20% unrecyclable catalysts reported by Ciacci et al. (2015). Concerning superalloys, Reck and Graedel (2012) estimated the EOL-RR to be of 68% circa 2010. We estimate the current collection yield to be of 40%, down from 68% a decade ago. Other applications are estimated not to be collected for recycling (Graedel et al., 2015). The following collection yields are reported in the dataset: alloys & solders, 40%; catalysts, 80%; and other industrial, military & energy applications, 0%.</p> | <p>Per sector; please refer to Supplementary Data</p> |
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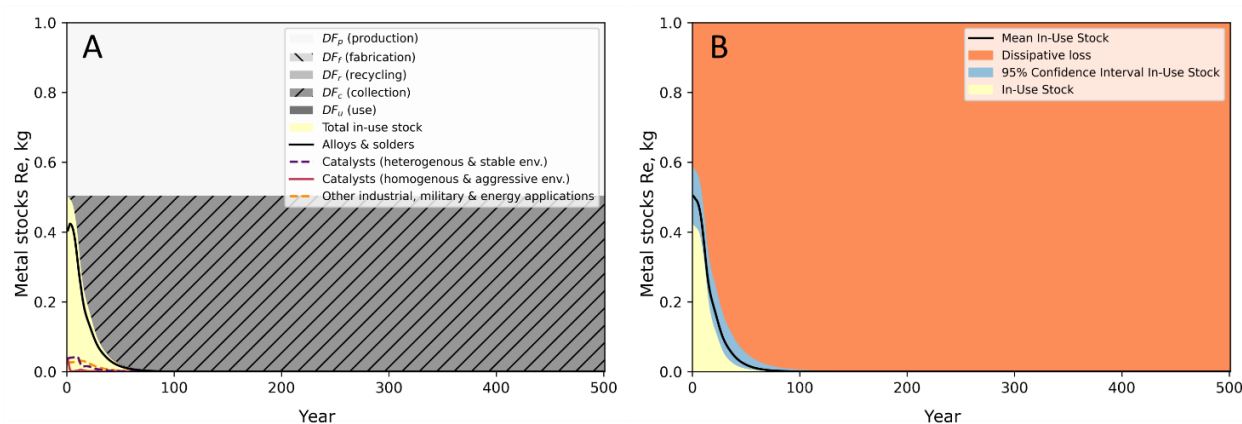


Figure B55. In-use stocks and losses of rhenium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.54 Osmium**Table B63. Osmium.**

| Osmium | Os, element number 76 | Uncertainty | | | | | | |
|--|--|---|-----|--|-----|-----------------------------|-----|---|
| End uses | <p>There is scarce information available for osmium. It is used in very small quantities globally (less than 1 ton per year) (Ciacci et al., 2015; Labbé and Dupuy, 2014). Its main uses are in electron microscopy, as a process catalyst in the chemical and pharmaceutical industries, as well as an alloying agent with other PGMs for various specialty applications such as medical implants (Ciacci et al., 2015). Johnson Matthey does not report statistics for osmium, and the end-use distribution of Ciacci et al. (2015) is reported in this dataset. Applications in electron microscopy are considered as a punctual application that is not recyclable currently (Ciacci et al., 2015). The end-uses of osmium, assumed to be representative of osmium uses in recent years, are the following:</p> <table><tr><td>Alloys & solders</td><td>10%</td></tr><tr><td>Catalysts (heterogenous & stable env.)</td><td>45%</td></tr><tr><td>Other punctual applications</td><td>45%</td></tr></table> | Alloys & solders | 10% | Catalysts (heterogenous & stable env.) | 45% | Other punctual applications | 45% | U1: 3 U2: 3 U3: 1 U4: 3 U5: 3 |
| Alloys & solders | 10% | | | | | | | |
| Catalysts (heterogenous & stable env.) | 45% | | | | | | | |
| Other punctual applications | 45% | | | | | | | |
| Production yield | <p>The mining yield is estimated to be 85% for all PGMs.</p> <p>The average concentration, smelting and refining yields for osmium are estimated to be the average values for PGMs reported by Nassar (2013) and are of 83.5%, 96% and 95%, respectively. The resulting production yield is 58%.</p> | U1: 3 U2: 3 U3: 1 U4: 3 U5: 1 | | | | | | |
| Fabrication and manufacturing | <p>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for osmium.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | |
| New scrap recovery | <p>N/A; 0% reported in this dataset.</p> | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Remelting | <p>N/A; 0% reported in this dataset.</p> | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | |
| Dissipation in use | <p>Based on Ciacci et al. (2015), it is estimated that 33% dissipation in use occurs from the use of osmium in catalysts (type B), and 100% dissipation in use occurs from the use of osmium in electron microscopy (type C).</p> | Per sector; please refer to Supplementary Data | | | | | | |
| Collection and sorting | <p>Osmium is not expected to be collected for recycling currently (Ciacci et al., 2015; UNEP, 2011).</p> | Per sector; please refer to Supplementary Data | | | | | | |

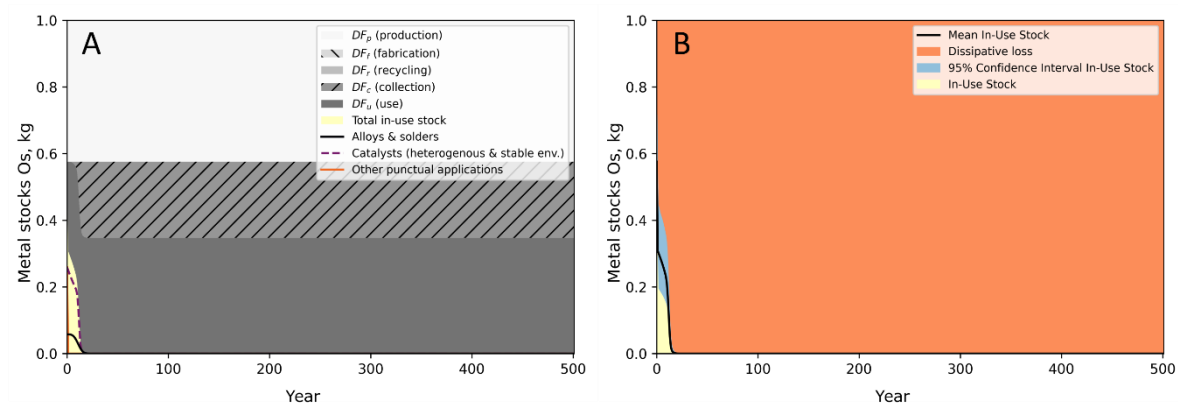


Figure B56. In-use stocks and losses of osmium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.55 Iridium

Note: We use the catalysts categories as proxies for ruthenium-iridium anodes and iridium crucibles based on the reported lifetimes for these applications to avoid generating additional single use sectors for industrial processes. The uses of iridium in crucibles is aggregated in the Catalysts (homogenous & aggressive env.) along with catalysts used by the chemical industry, and its uses in the electrochemical industry (anodes coating) was reported in the Catalysts (heterogeneous & stable env.) sector.

Table B64. Iridium.

| Iridium | Ir, element number 77 | Uncertainty | | | | | | | | | | | | |
|--|---|---|----|---|-----|--|-----|----------------------|----|--|-----|---------------------|----|---|
| End uses | <p>Iridium is mostly used in electrical, electrochemical, and chemical industries, as well as in jewelry, medical applications, automotive industry (especially for spark plugs), and a range of miscellaneous applications (BRGM, 2020a; Ciacci et al., 2015). Johnson Matthey reports demand statistics for iridium for the year 2019 (Johnson Matthey, 2020b). The BRGM also provides a more disaggregated distribution in end-use sectors for the same year (BRGM, 2020a), based on a report of SFA Oxford (2020). Both sets of data cover a total of 8.2 tons of iridium (as demand for the former, and as consumed for the latter), and present similar distributions. The data reported by BRGM (2020a) is used to establish the end-use distribution of iridium.</p> <p>The use of iridium by the electrical industries is considered to be mostly in crucibles used to grow high purity crystals (Ciacci et al., 2015). Iridium is also used as a catalyst in the chemical industry, for which an estimated lifetime of 0.1 to 5 years is reported (Nassar, 2013), and as a coating for dimensionally stable anodes in the electrochemical industry along with ruthenium, for which a lifetime of 5 to 8 years is reported (Nassar, 2013).</p> <p>The contemporary use of iridium in the automotive industry seems to be mostly for high-end spark plugs, which are classified as Other miscellaneous applications considering that they must be replaced a few times over the lifetime of vehicles. Other applications include alloys and superalloys used in a variety of applications; these are aggregated in the Other industrial, military & energy applications. The following end-use distribution is representative of end-uses of iridium in 2019:</p> <table><tr><td>Biomedical & dental</td><td>9%</td></tr><tr><td>Catalysts (heterogeneous & stable env.)</td><td>26%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>39%</td></tr><tr><td>Jewelry & investment</td><td>4%</td></tr><tr><td>Other industrial, military & energy applications</td><td>16%</td></tr><tr><td>Other miscellaneous</td><td>6%</td></tr></table> | Biomedical & dental | 9% | Catalysts (heterogeneous & stable env.) | 26% | Catalysts (homogenous & aggressive env.) | 39% | Jewelry & investment | 4% | Other industrial, military & energy applications | 16% | Other miscellaneous | 6% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 2 |
| Biomedical & dental | 9% | | | | | | | | | | | | | |
| Catalysts (heterogeneous & stable env.) | 26% | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 39% | | | | | | | | | | | | | |
| Jewelry & investment | 4% | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 16% | | | | | | | | | | | | | |
| Other miscellaneous | 6% | | | | | | | | | | | | | |
| Production yield | <p>The mining yield is estimated to be 85% for all PGMs.</p> <p>The average concentration, smelting and refining yields for iridium correspond to the average values reported by Nassar (2013) and are of 73.5%, 96% and 96%, respectively. The resulting production yield is 58%.</p> | U1: 2 U2: 3 U3: 1 U4: 2 U5: 1 | | | | | | | | | | | | |
| Fabrication and manufacturing | <p>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for iridium.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | |

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| New scrap recovery | N/A; 0% reported in this dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | A remelting yield of 96% is assumed (same as refining). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | The dissipation rates for iridium are calculated based on Ciacci et al. (2015). The dissipation in use rate for catalysts is calculated considering the share of electronic and chemical industries included in the sector, for which dissipation in use rates of 33% and 5% are estimated. The resulting dissipation rates for iridium end-use sectors are the following: catalysts (homogenous & aggressive env.) (including iridium crucibles), 26%; catalysts (heterogeneous & stable env.) (proxy for ruthenium-iridium anodes), 8%; other miscellaneous (spark plugs), 5%. Other uses are considered not to be dissipated during use. | Per sector; please refer to Supplementary Data |
| Collection and sorting | <p>An EoL-RR of 20-30% was estimated for iridium circa 2010 (UNEP, 2011). Assuming a constant distribution of end-uses over time, the data reported by Nassar (2013) fall quite below this value, and the estimates are updated with additional information. Notably, an EoL-RR of 95% is assumed by Ciacci et al. (2015) for the closed loop recycling of iridium crucibles that have not been dissipated during use. An EoL-RR of 5% is considered for medical applications based on the lowest bound of estimated French statistics (BRGM, 2020a). Finally, an EoL-RR of 0% for spark plugs, 7.5% for other industrial applications, and 45% for iridium uses in the chemical and electrochemical industry is considered (Nassar, 2013; UNEP, 2011). The latter is the same as that of ruthenium used in the same application. Similarly, we assume an EoL-RR of 90% for jewelry, based on the lower bound of EoL-RRs reported for other PGMs used in that application. The EoL-RR for electronic and chemical industrial uses are corrected based on their respective shares of the sector to provide the aggregated value for catalysts sectors. Finally, the collection yields are extrapolated considering a remelting yield of 96%, and are the following: Catalysts (homogenous & aggressive env.), 87%; Catalysts (homogenous & aggressive env.), 47%; Jewelry & investment, 94%; Other miscellaneous (spark plugs), 0%; Biomedical & dental, 5%; and Other industrial, military & energy applications, 7.5%.</p> <p>Assuming a constant distribution of end-uses over time, these collection yields suggest a global EoL-RR for iridium higher than the 30% reported in the UNEP report, which may warrant additional investigations.</p> | Per sector; please refer to Supplementary Data |

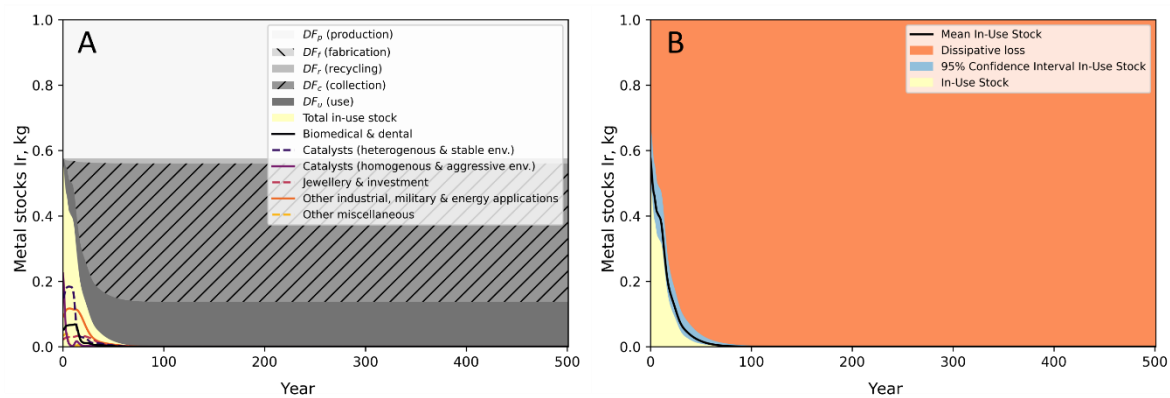


Figure B57. In-use stocks and losses of iridium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.56 Platinum**Table B65. Platinum.**

| Platinum | Pt, element number 78 | Uncertainty | | | | | | | | | | | | | | | | | | | | |
|--|--|---|----|---|----|--|-----|-------------|----|---------------------|----|----------------------|-----|--|----|---------------------|----|-----------------------------|------|-----------|-----|---|
| End uses | <p>Platinum is primarily used as a catalytic converter in exhaust pipes of vehicles, in jewelry and in investment products. Other uses include catalysts used in the chemical industry, medical and dental applications and in the glass manufacturing industry (Ciacci et al., 2015; Graedel et al., 2013).</p> <p>The end-use distribution for platinum is based on Matthey Johnson’s reports (Johnson Matthey, 2020a, 2015). It is assumed that 10% of the demand for medical applications are for anti-cancer drugs based on Ciacci et al. (2015), and these are classified as pharmaceuticals. Moreover, the other uses of platinum are split half and half between other miscellaneous and other industrial, military & energy applications categories based on qualitative and quantitative information provided by Ciacci et al. (2015) in order to represent the different lifetimes of potential applications such as spark plugs, turbine blade coatings and oxygen sensors. Finally, catalysts used in the petroleum industries are split between the two categories of catalysts to reflect the variability of their potential lifetimes, i.e. 1 to 12 years (Nassar, 2013).</p> <p>Given that platinum has been continuously used in investment products over a 10-year period, investment was considered in the end-use distribution accordingly with the methodology presented in section B.2.3.2. The following distribution is estimated to be representative of 2019:</p> <table><tr><td>Biomedical & dental</td><td>3%</td></tr><tr><td>Catalysts (heterogeneous & stable env.)</td><td>2%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>10%</td></tr><tr><td>Electronics</td><td>3%</td></tr><tr><td>Glass manufacturing</td><td>5%</td></tr><tr><td>Jewelry & investment</td><td>33%</td></tr><tr><td>Other industrial, military & energy applications</td><td>4%</td></tr><tr><td>Other miscellaneous</td><td>4%</td></tr><tr><td>Pharmaceuticals & cosmetics</td><td>0.3%</td></tr><tr><td>Transport</td><td>37%</td></tr></table> | Biomedical & dental | 3% | Catalysts (heterogeneous & stable env.) | 2% | Catalysts (homogenous & aggressive env.) | 10% | Electronics | 3% | Glass manufacturing | 5% | Jewelry & investment | 33% | Other industrial, military & energy applications | 4% | Other miscellaneous | 4% | Pharmaceuticals & cosmetics | 0.3% | Transport | 37% | U1: 2 U2: 1 U3: 1 U4: 3 U5: 1 |
| Biomedical & dental | 3% | | | | | | | | | | | | | | | | | | | | | |
| Catalysts (heterogeneous & stable env.) | 2% | | | | | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 10% | | | | | | | | | | | | | | | | | | | | | |
| Electronics | 3% | | | | | | | | | | | | | | | | | | | | | |
| Glass manufacturing | 5% | | | | | | | | | | | | | | | | | | | | | |
| Jewelry & investment | 33% | | | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 4% | | | | | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 4% | | | | | | | | | | | | | | | | | | | | | |
| Pharmaceuticals & cosmetics | 0.3% | | | | | | | | | | | | | | | | | | | | | |
| Transport | 37% | | | | | | | | | | | | | | | | | | | | | |
| Production yield | <p>The mining yield is estimated to be 85% for all PGMs.</p> <p>The average concentration, smelting and refining yields for platinum correspond to the average values reported by Nassar (2013) and are of 84.2%, 96% and 99.25%, respectively. The resulting production yield is of 68%.</p> | U1: 2 U2: 3 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | <p>It is assumed that fabrication yields for all PGMs are close to 100% (including new scrap recovery). A yield of 100% is reported for platinum.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | | | | | | | | | |
| New scrap recovery | <p>N/A; 0% reported in this dataset.</p> | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | | | | | | | |

| | | |
|-------------------------------|---|---|
| Remelting | A remelting yield of 99.25% is assumed (same as refining). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | The dissipation in use for platinum are estimated based on Nassar (2013) and Ciacci et al. (2015). The dissipation in use rate for catalysts is determined considering the relative share of catalysts used in the chemical and petroleum industries that are aggregated in the two distinct catalysts sectors. The estimated dissipation in use rates are the following: Catalysts (heterogeneous & stable env.), 11%; Catalysts (homogenous & aggressive env.), 36%; Glass manufacturing, 1%; Other industrial, military & energy applications, 10%; Other miscellaneous, 17%; Pharmaceuticals & cosmetics, 100%; and Transport, 2%. No dissipation in use is reported for other sectors. | Per sector; please refer to Supplementary Data |
| Collection and sorting | Between 60 and 70% of EOL platinum scraps are estimated to be recycled (BRGM, 2017k). The EOL-RR ranges reported by (Nassar, 2013) and (UNEP, 2011) are considered to establish collection yields, considering the remelting yield of 99.25%. For the platinum content of auto catalysts, an average global EOL-RR of 60% is considered (as for palladium), slightly higher than the estimated range of 50-55% circa 2010 (UNEP, 2011). The EoL-RR for the investment and jewelry category is calculated considering an EoL-RR of 100% for the former, and 95% for the latter, and considering their respective shares for that sector. The following collection yields are reported in the dataset: Biomedical & dental, 18%; Catalysts (heterogeneous & stable env.), 99%; Catalysts (homogenous & aggressive env.), 97%; Electronics, 19%; Glass manufacturing, 99%; Jewelry & investment, 97%; Other industrial, military & energy applications, 15%; Other miscellaneous, 15%; Pharmaceuticals & cosmetics, 0%; and Transport, 60%. Assuming a constant distribution of end-uses over time, the reported yields suggest a global EoL-RR of approximately 65%, and are thus estimated to be reasonably representative of the current yields. | Per sector; please refer to Supplementary Data |

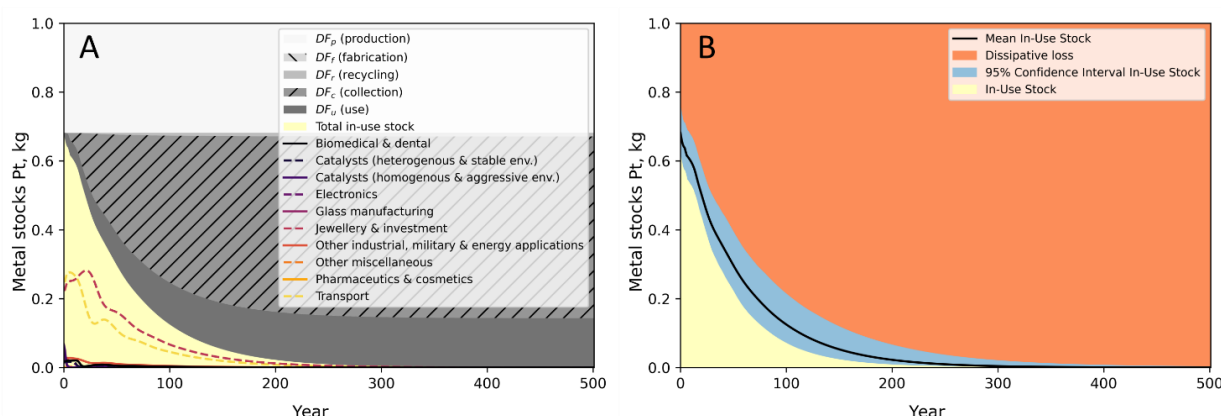


Figure B58. In-use stocks and losses of platinum over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.57 Gold**Table B66. Gold.**

| Gold | Au, element number 79 | Uncertainty | | | | | | | | |
|--|--|-------------------------------------|------|-------------|----|----------------------|-----|--|----|---|
| End uses | <p>The World Gold Council provides global end-use statistics for gold (World Gold Council, 2020). In this dataset, investment products are considered as a functional end-use of gold. Given the importance of the use of gold as a financial product, demand for gold may be influenced by the economic conjuncture. While demand for the jewelry and financial products fluctuated over the analyzed period, an important decline of the use of gold in dentistry applications (about 70%) and in other industrial applications (about 45%) can be observed over between 2010 to 2019, which could be attributed to e.g. substitution or an increase in efficiency. The demand for gold in the electronics sector has steadily decreased over the years, for a total of about 20% decrease between 2010 to 2019. At the same time, the total demand for gold remained quite stable over the years, with an average of approximately 4 450 tons per year.</p> <p>In order to flatten out the effects of economic conjuncture on the demand for financial products, the 10-years average values from 2010 to 2019 are used to measure its average share of end uses. The other end-uses for the year 2019 are balanced to account for the remaining share of end uses. This method is also used for other precious metals used in investment (cf. section B.2.3.2).</p> <p>The following distribution is representative of the year 2019 based on demand statistics (World Gold Council, 2021):</p> <table><tr><td>Biomedical & dental</td><td>0.3%</td></tr><tr><td>Electronics</td><td>6%</td></tr><tr><td>Jewelry & investment</td><td>92%</td></tr><tr><td>Other industrial, military & energy applications</td><td>1%</td></tr></table> <p>Out of the 92% reported for the jewelry and financial products, about 49% is for jewelry, and about 42% for financial products (including private investment products, gold-backed exchange traded funds and demand by central banks).</p> | Biomedical & dental | 0.3% | Electronics | 6% | Jewelry & investment | 92% | Other industrial, military & energy applications | 1% | U1: 2 U2: 1 U3: 1 U4: 2 U5: 1 |
| | Biomedical & dental | 0.3% | | | | | | | | |
| Electronics | 6% | | | | | | | | | |
| Jewelry & investment | 92% | | | | | | | | | |
| Other industrial, military & energy applications | 1% | | | | | | | | | |
| Production yield | <p>There is scarce information on primary gold production efficiency in the scientific literature. Nassar et al. (2012) assumes processing losses of 5% after recovery. The US statistics in 1998 suggest an efficiency of refining of 98.2% (USGS, 2004b), which seems to correspond to the refining of doré bars.</p> <p>A small online survey revealed that there are many technical reports available for gold producing companies, which could be ideally consulted for an exhaustive assessment of the gold production yield. In order to obtain a more solid estimation of the production yield, several technical reports for various gold mining sites were consulted for this dataset (Base Met Labs, 2017; BBA, 2020; InnovExplo, 2013; Mannard and Ng, 2016; Snowden, 2016; Zandonai, 2017). Some of these reports cover multiple</p> | U1: 3 U2: 1 U3: 1 U4: 2 U5: 1 | | | | | | | | |

| | | |
|--------------------------------------|---|---|
| | <p>mining sites. Moreover, the annual reports from Freeport-McMoRan provide yearly recovery yields for their mining operations in Indonesia (Freeport-McMoRan, 2019, 2016).</p> <p>Alike for PGMs, some resources are expected to never reach the mill due to various factors (e.g., pillar losses in underground mining, mining losses), in addition to the mine-call-factors (Nassar, 2013). The reported ore recovery from the different drilling holes at the various mining sites range between 80% and 100% (excluding the most superficial layers, for which lower recoveries are sometimes reported). An estimated 85% mining yield is considered for this dataset, which is assumed to cover all extraction losses across both open pit and underground mining operations.</p> <p>Moreover, the reported post-mining recovery yields range between 75 and 100%. The total gold recovery yields for gold production in various reports range between 52% and 97%, which are generally observed to be lower for lower grade ores across the studied mining projects. For example, the Selinsing Gold Mine had its recovery rate decline from 92.9% to 67.4% while its average ore head grade declined from 4.31 to 0.88 g Au/t between 2011 and 2016 (Snowden, 2016). The lowest reported yield (52%) is from the Don Mario mine in Bolivia where gold is co-produced along with copper and silver (Zandonai, 2017). The lower yields generally seem to correspond to lower grade ores that are being processed at different plants. An average beneficiation and concentration (from ores to doré bars) yield of 87.5% is considered, which is lower than the 95% estimate of Nassar et al. (2012).</p> <p>Finally, a refining yield of 98.5% from doré bars to pure gold is considered, similar to those reported for the valuable PGMs, and similar to that of 98.2% reported for the US in year 1998. Based on this information, it is estimated that the global production yield of gold is of 73%.</p> | |
| Fabrication and manufacturing | <p>The processing yields for fabrication and manufacturing, new scrap recovery, collection and remelting are calculated using the US statistics of 1998 (USGS, 2004a). These are assumed to be reasonably representative of the global processing yields given the long history of gold use in the US.</p> <p>The fabrication rate was calculated taking into account investment and refined bullions, which are fabricated with a yield of 100%. The yields for investment products and for other products were normalized using the end-uses distribution reported in this dataset. A yield of 100% was considered for investment products, representing 44% of total demand; and a yield of 82% was calculated for other applications, with a new scrap recovery of 90%. The resulting fabrication and manufacturing yield is of 90%.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | 90%, calculated from US statistics of 1998 (USGS, 2004a). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Remelting | 98%, calculated from US statistics of 1998 (USGS, 2004a). | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |

| | | |
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| Dissipation in use | No dissipative uses of gold were considered, although there might be minor losses attributed to uses in decorative applications and as flake and dust in food or drinks (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |
| Collection and sorting | The EoL-RR reported by Nassar et al. (2012) were considered to extrapolate collection yields given a remelting yield of 98%. The EoL-RR of the jewelry and investment category was corrected assuming a collection rate of 100% for financial products along with 95% jewelry EoL-RR reported by Nassar et al. (2012). The resulting collection rates are the following: Biomedical & dental, 18%; Electronics, 13%, Jewelry & investment, 99%, and Other industrial, military & energy applications, 82%. | Per sector; please refer to Supplementary Data |

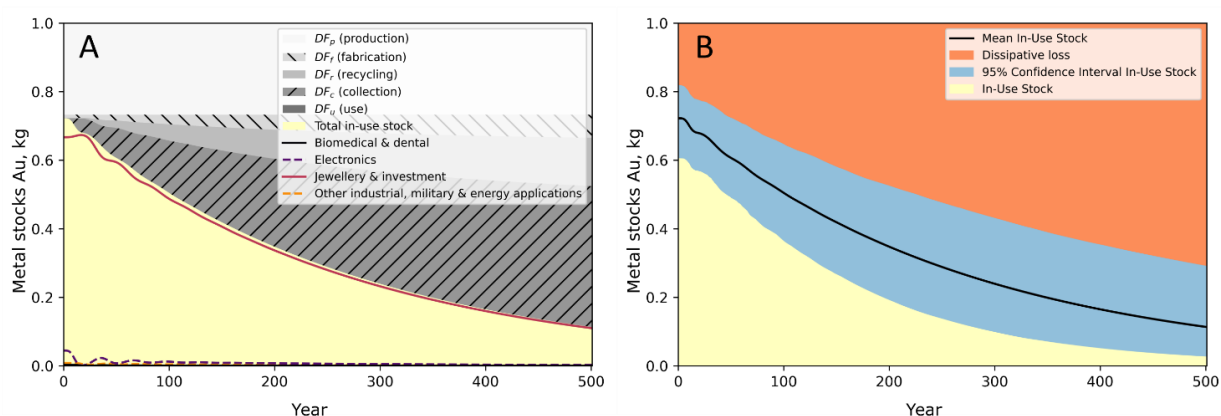


Figure B59. In-use stocks and losses of gold over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.58 Mercury**Table B67. Mercury.**

| Mercury | Hg, element number 80 | Uncertainty | | | | | | | | | | | | | | | | | | | | |
|--|---|---|----|--|----|---------------------|----|--|-----|-----------|----|-------------|----|----------|----|--|----|---------------------|----|-----------------------------|-----|---|
| End uses | <p>The latest UN Environment’s report on global mercury supply, trade and demand include a detailed end-use distribution for the year 2015 (UN Environment, 2017). The mean global consumption values as published in table 17 of the UN Environment report are used to obtain the end-use distribution for mercury. The most important uses are in artisanal gold mining operations and in industrial applications. Part of the chlor-alkali production is done using liquid mercury in electrolytic cells to act as a cathode, and mercuric chloride on carbon pellets is used as a catalyst to produce vinyl chloride monomers (VCM) (Maxson, 2006; UN Environment, 2017). Other uses include batteries, dental applications, measuring and control devices such as thermometers, lamps, electrical and electronic devices, and mercury compounds used in various applications (UN Environment, 2017).</p> <p>Measuring and control devices, estimated to have a lifetime of 20 years (Panousi et al., 2016), are classified as Other industrial applications. Moreover, 75% of Hg compounds are assumed to be used in dissipative applications (type A and B) based on the consulted literature, including agricultural, pharmaceutical and cosmetic applications: these are aggregated into the agricultural & environmental applications. Mercury use for VCM production is classified as a Catalysts (homogenous & aggressive env.), and that for chlor-alkali production, as a chemical (based on the expected lifetime for that end use). Small scale artisanal gold mining is classified as a punctual dissipative application. The following distribution is estimated to be representative of 2015:</p> <table><tr><td>Agricultural & environmental applications</td><td>4%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>5%</td></tr><tr><td>Biomedical & dental</td><td>6%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>26%</td></tr><tr><td>Chemicals</td><td>6%</td></tr><tr><td>Electronics</td><td>3%</td></tr><tr><td>Lighting</td><td>3%</td></tr><tr><td>Other industrial, military & energy applications</td><td>7%</td></tr><tr><td>Other miscellaneous</td><td>4%</td></tr><tr><td>Other punctual applications</td><td>37%</td></tr></table> <p><u>Note:</u> Given the multiple applications specific to mercury, these are aggregated in existing end-use categories used as proxies (as described above), considering the expected lifetimes for each of these applications.</p> | Agricultural & environmental applications | 4% | Batteries (consumer electronics & lead acid) | 5% | Biomedical & dental | 6% | Catalysts (homogenous & aggressive env.) | 26% | Chemicals | 6% | Electronics | 3% | Lighting | 3% | Other industrial, military & energy applications | 7% | Other miscellaneous | 4% | Other punctual applications | 37% | U1: 2 U2: 2 U3: 1 U4: 2 U5: 2 |
| Agricultural & environmental applications | 4% | | | | | | | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 5% | | | | | | | | | | | | | | | | | | | | | |
| Biomedical & dental | 6% | | | | | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 26% | | | | | | | | | | | | | | | | | | | | | |
| Chemicals | 6% | | | | | | | | | | | | | | | | | | | | | |
| Electronics | 3% | | | | | | | | | | | | | | | | | | | | | |
| Lighting | 3% | | | | | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 7% | | | | | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 4% | | | | | | | | | | | | | | | | | | | | | |
| Other punctual applications | 37% | | | | | | | | | | | | | | | | | | | | | |
| Production yield | <p>Estimating the yield of primary production is uneasy as mercury can be obtained from various sources and is not always marketed due to its toxicity. For instance, mercury can be obtained from the de-contamination of fossil fuels, which is widespread since it is highly volatile and hazardous for human health and the environment (UN Environment, 2018, 2017). In</p> | U1: 3 U2: 4 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | | | | | | | | | |

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| | <p>an effort to decrease Hg emissions to the environment, severe regulations limit the use and exports of mercury in many developed countries such as those in Europe and the US (UN Environment, 2017; USGS, 2020). For such reason, mercury captured by e.g. air decontamination or as a contaminant from various non-ferrous ores may be stored or landfilled as a hazardous waste instead of being put on the market (UN Environment, 2017). Such potential mercury production routes are often considered as a contaminant rather than as a resource.</p> <p>We here consider only primary mercury production from ore mining targeting mercury. There is scarce information on the mining and concentrating processes (cf. UN Environment, 2018, box A3.6.11, p. 3-74). Up to 20-25% of mercury is lost in artisanal mining operations in Mexico (UN Environment, 2017). Still, it is assumed that artisanal mercury mining covers only a fraction of total mercury production (including within Mexico), and China produced about 25 times more mercury than Mexico in 2019 according to (USGS, 2020). Wilburn (2013) reports a recovery of 95% from mined ores based on Nowak and Singer (1995). The statistics for the US production of mercury for the year 1990 suggest a production yield of 86.2% (Sznoppek and Goonan, 2000). Given the disparate and scarce available information, the values of 10% mining and 5% refining losses reported by Panousi et al. (2016) are considered as the best estimates available for global mercury production, suggesting a yield of 86%.</p> | |
| Fabrication and manufacturing | <p>Many uses of mercury do not necessitate an industrial fabrication and manufacturing phase. US stats for 2010 suggest a yield of 96% for products containing mercury (i.e. without industrial and artisanal gold mining), with a recovery of new scraps of 100% (Wilburn, 2013).</p> <p>A global yield of 95% is assumed, assuming that 5% mercury is lost to e.g. vaporization between the production and use phase, e.g. due to the large quantity used in the informal sector, or during the maintenance operations to renew mercury in industrial applications. It should be noted that, in such cases, the losses do not necessarily result from a fabrication process per se. The yield is assumed to include new scrap recovery and remelting, if ever it occurs.</p> | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| New scrap recovery | 0% is reported in the dataset (it is assumed to be included in the fabrication and manufacturing yield). Some recovery of new scraps does occur, e.g. in the US (Wilburn, 2013). | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 |
| Remelting | 95 % (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 |
| Dissipation in use | All of mercury used for artisanal and small-scale gold mining is expected to be dissipated during use (type B dissipation), and a rate of 100% is reported (Ciacci et al., 2015; UN Environment, 2017). We also consider that all of the mercury used in agricultural, environmental, pharmaceutical or cosmetic products is lost during use. Moreover, about 2% of mercury is thought to be dissipated during its use for the production of VCM (dissipation in use of type B), 31% during the production of chlorine caustic soda, and 0% for other uses (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data |

| | | |
|-------------------------------|---|---|
| Collection and sorting | <p>About 50% of the mercury used in industrial processes is recycled (UN Environment, 2017). The EOL-RR for non-dissipative applications are reported to be 15% by Maxson (2006), which were also considered by Panousi et al. (2016). Considering a remelting yield of 95%, and the different aggregation realized in this dataset in comparison to Panousi et al. (2016), the collection yields for the different applications are estimated to be the following: Catalysts (homogenous & aggressive env.) (proxy for VCM production), 53%; Chemicals (proxy for chlorine caustic soda manufacturing); 53%, other non-dissipative uses, 16%; and 0% for all of the dissipative uses including environmental & agricultural applications as well as artisanal gold mining.</p> | <p>Per sector; please refer to Supplementary Data</p> |
|-------------------------------|---|---|

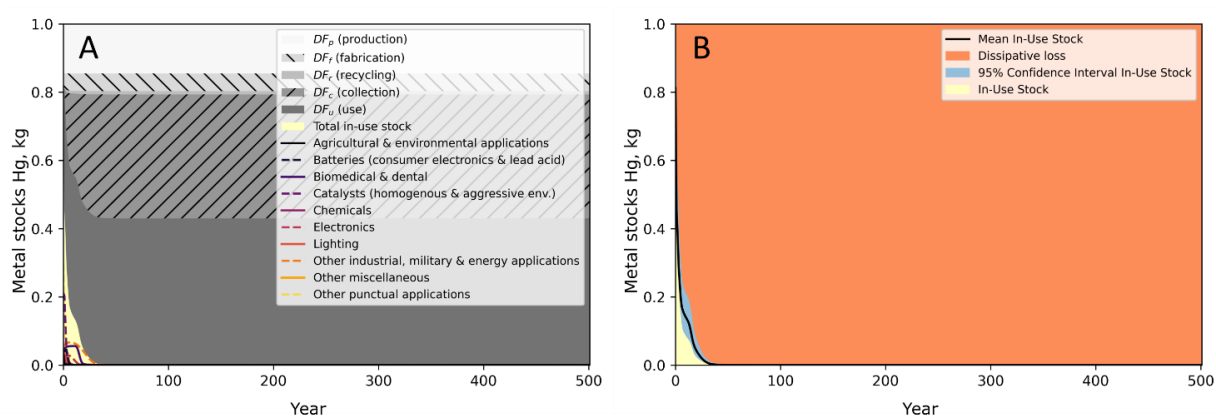


Figure B60. In-use stocks and losses of mercury over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.59 Thallium**Table B68. Thallium.**

| Thallium | Tl, element number 81 | Uncertainty | | | | |
|-------------------------------|---|---|-----|---------------------|-----|---|
| End uses | <p>Scarce quantitative information is available for thallium, and it was not included in the latest European Commission’s criticality studies (European Commission, 2020c, 2020a). Thallium is a highly toxic metal and its uses are heavily regulated (USGS, 2020). Its most important uses are limited to photoelectric cells, infrared optical materials, and low melting glasses (USGS, 2020).</p> <p>Is this dataset, the end-use distribution suggested by Panousi et al. (2016) based on an informed estimate, is reported:</p> <table><tr><td>Electronics</td><td>90%</td></tr><tr><td>Other miscellaneous</td><td>10%</td></tr></table> | Electronics | 90% | Other miscellaneous | 10% | U1: 3 U2: 4 U3: 1 U4: 3 U5: 2 |
| Electronics | 90% | | | | | |
| Other miscellaneous | 10% | | | | | |
| Production yield | <p>Thallium is present in trace amounts in copper, lead, zinc other sulfide ores from which it is seldom extracted as a by-product (USGS, 2020). Alike mercury, much thallium is mined out, but is considered to be a contaminant rather than a resource in most cases, given its toxicity and the paucity of end uses. Global production was estimated to be below 8000 kg in 2019, while several million of kilograms are present in the reserves of the different ores (e.g., zinc) in which it is found (USGS, 2020).</p> <p>Without further information, it is assumed that only the thallium targeted for extraction is to be considered as a resource, alike for mercury, and an informed estimate of 70% is considered for the production yield (Panousi et al., 2016).</p> | U1: 3 U2: 4 U3: 1 U4: 3 U5: 1 | | | | |
| Fabrication and manufacturing | 100% (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | |
| New scrap recovery | N/A, 0% in the dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | |
| Remelting | N/A, 0% in the dataset | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | |
| Dissipation in use | 0% for both application sectors (Ciacci et al., 2015) | Per sector; please refer to Supplementary Data | | | | |
| Collection and sorting | 0% (Ciacci et al., 2015; Panousi et al., 2016). | Per sector; please refer to Supplementary Data | | | | |

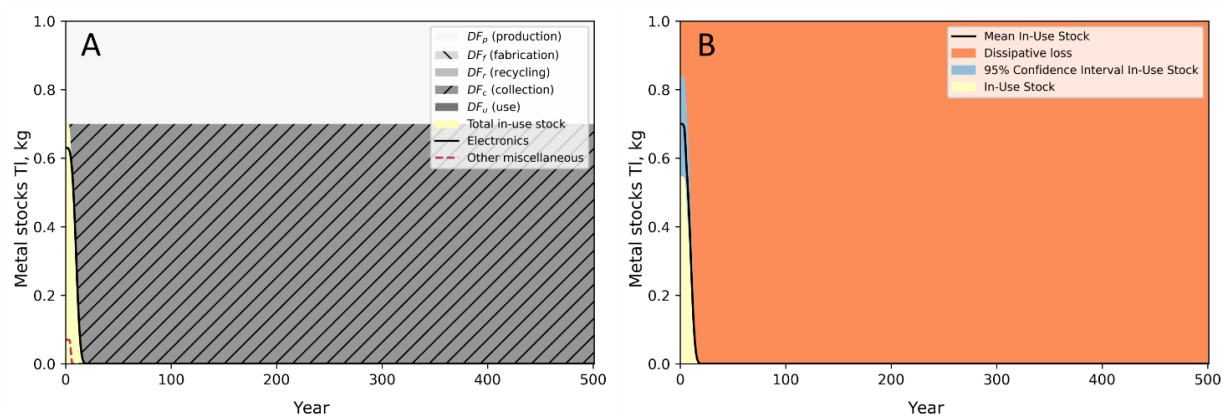


Figure B61. In-use stocks and losses of thallium over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.60 Lead**Table B69. Lead.**

| Lead | Pb, element number 82 | Uncertainty | | | | | | | | | | | | | | |
|--|--|---|----|--|-----|--------------|----|----------------|----|--|----|-----------------------------|----|-------|----|---|
| End-uses | <p>Global lead end-use distributions are available for several years, often based on the International Lead and Zinc Study Group (ILZSG). For example, end-use distributions are available for 2014 (Ciacci et al., 2015), 2016-2020 (average) (International Lead and Zinc Study Group, 2021b). Another single year distribution is reported by the International Lead Association for the year 2017 (Wilson, 2019). The most important end-use of lead is in batteries, with over 80% of its use. Based on the consulted literature, the 5% other end-uses reported by Wilson (2019) is partitioned between alloys (including solders) (2%), cable sheathing (1%), gasoline additive (0.3%), and others (1.7%). Pigments and paint are added to the paint category. Cable sheathing are aggregated in the infrastructure category, and gasoline additives are aggregated in other punctual uses along with ammunitions. Rolled and sheet products are thought to be used mostly in construction or industrial installations (Ciacci et al., 2015; European Commission, 2020c) and are added to the construction sector. The following distribution is estimated to be representative of years 2017-2019:</p> <table><tr><td>Alloys & solders</td><td>2%</td></tr><tr><td>Batteries (consumer electronics & lead acid)</td><td>86%</td></tr><tr><td>Construction</td><td>4%</td></tr><tr><td>Infrastructure</td><td>1%</td></tr><tr><td>Other industrial, military & energy applications</td><td>2%</td></tr><tr><td>Other punctual applications</td><td>2%</td></tr><tr><td>Paint</td><td>3%</td></tr></table> | Alloys & solders | 2% | Batteries (consumer electronics & lead acid) | 86% | Construction | 4% | Infrastructure | 1% | Other industrial, military & energy applications | 2% | Other punctual applications | 2% | Paint | 3% | U1: 2 U2: 1 U3: 1 U4: 1 U5: 1 |
| Alloys & solders | 2% | | | | | | | | | | | | | | | |
| Batteries (consumer electronics & lead acid) | 86% | | | | | | | | | | | | | | | |
| Construction | 4% | | | | | | | | | | | | | | | |
| Infrastructure | 1% | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 2% | | | | | | | | | | | | | | | |
| Other punctual applications | 2% | | | | | | | | | | | | | | | |
| Paint | 3% | | | | | | | | | | | | | | | |
| Production yield | 89% (Helbig et al., 2020, based on Mao et al., 2008a) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 94% (Helbig et al., 2020, based on Mao et al., 2008a) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | |
| New scrap recovery | 80% (Helbig et al., 2020, based on Mao et al., 2008a) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | |
| Remelting | 100% (Helbig et al., 2020, based on Mao et al., 2008a) | U1: 1 U2: 4 U3: 1 U4: 2 U5: 2 | | | | | | | | | | | | | | |
| Dissipation in use | Some lead uses are considered to be dissipative. Yellow paint used in road marking and rolled products are considered to be partly dissipated in use (type B dissipation), while gasoline additives and ammunitions are completely lost to the environment when they are used (dissipation type A) (Ciacci et al., 2015). Based on the latter authors, we estimate dissipation in use rates of 20% for pigments and paint (road paint), 5% for the construction sector, and 100% for other punctual applications. Other uses are not considered to be dissipative (Ciacci et al., 2015). | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | |

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| Collection and sorting | <p>Lead is one of the most recycled metal, with nearly 60% of the supply originating from secondary sources according to the International Lead Association (Wilson, 2019). Helbig et al. (2020) calculated a global collection yield of 66% in year 2000 based on Mao et al. (2008a). Due to the severe regulations surrounding the uses of lead and the progressive elimination of dissipative uses of lead, the EOL-RR has seemingly increased in the past two decades in comparison to that in 2000. We estimate that currently, 85% of lead batteries are collected and functionally recycled based on Harper et al. (2015) and Wilson (2019), and that 10% of cable sheathing (included in infrastructure) and 60% of construction and alloys & solders applications are currently collected for recycling based on Ciacci et al. (2015) and Harper et al. (2015).</p> | Per sector; please refer to Supplementary Data |
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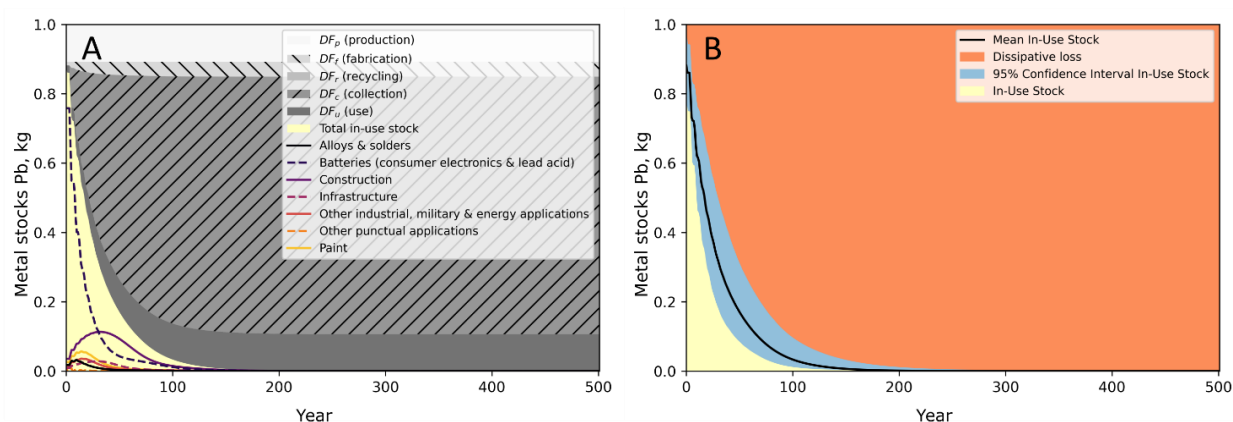


Figure B62. In-use stocks and losses of lead over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

B.3.2.61 Bismuth**Table B70. Bismuth.**

| Bismuth | Bi, element number 83 | Uncertainty |
|-----------------|---|--|
| End uses | <p>Bismuth is mostly used in various chemicals (approximately 50-60% of its uses) in a wide variety of products such as pharmaceutical and cosmetic products, X-Ray shielding in medical applications, pigments in paints, ceramics and plastics, electronic ceramics and flame retardants for plastic products, amongst others (Burgess et al., 2014; European Commission, 2020a; Raja, 2009; USGS, 2020). It is also used as a metallurgical additive in a variety of alloys and solders as well as a component of frit material in ceramic glass enamels. Other uses include extreme pressure greases and lubricants, brake linings, clutch pads, fluorescent lamps and fireworks (Burgess et al., 2014; Raja, 2009; USGS, 2020).</p> <p>Global bismuth end-uses are available for the fiscal year 2006-2007 (Graedel et al., 2013; Panousi et al., 2016) and 2008 (Raja, 2009), and the demand for metallurgical and chemical bismuth compounds is available for year 2014 (Burgess et al., 2014). The end-uses reported in this dataset are based on the end-uses reported by Raja (2009) and Panousi et al. (2016), which are updated with quantitative and qualitative information (Burgess et al., 2014; Ciacci et al., 2015; European Commission, 2020a; Fortune Minerals, 2020; USGS, 2020).</p> <p>Special attention is spent on attributing chemicals to actual end-use categories given their important share of the reported bismuth uses. Notably, 25% bismuth uses are attributed to the automotive industry, as windshield frits alone could represent approximately 3000 to 5 000 tons of bismuth used annually considering that about 50 grams are used “for most of the 95 million cars produced annually” (Fortune Minerals, 2020). Moreover, parts of chemicals are expected to be used in dissipative applications such as animal feed, cosmetics and pharmaceutical products. Ciacci et al. (2015) assumed that one third of chemical uses were dissipated in use. Based on that information, we assumed that 10% out of chemical uses of bismuth, including subsalicylates (7% of total bismuth use according to Burgess et al., 2014), are used in pharmaceutical and cosmetics products, as well 5% in agricultural & environmental applications. Another 2% of bismuth is estimated to be used in a range of Other punctual applications, including e.g. lubricants and fireworks. The remainder of bismuth chemicals is considered to be used in plastics (as pigments and flame retardant), ceramics and electronic ceramic materials, and catalysts (Raja, 2009). We assume that 5% of bismuth is used as catalysts, and the remainder share of chemicals is split half and half between Other industrial, military & energy applications and Other miscellaneous applications to reflect the diversity of potential uses. Finally, we estimate that 5% out of the 33% considered to be used as alloys are used for bullets, based on Ciacci et al. (2015). These are also aggregated in the Other punctual applications category.</p> | <p>U1: 3 U2: 1 U3: 1 U4: 2 U5: 2</p> |

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|--|---|---|----|------------------|-----|--|----|--|-----|---------------------|-----|-----------------------------|----|---------------------------|-----|-----------|-----|--|
| | <p>Based on this information, the following distribution is estimated to be representative of the global end-uses of bismuth around 2010-2019:</p> <table><tr><td>Agricultural & environmental applications</td><td>5%</td></tr><tr><td>Alloys & solders</td><td>28%</td></tr><tr><td>Catalysts (homogenous & aggressive env.)</td><td>5%</td></tr><tr><td>Other industrial, military & energy applications</td><td>10%</td></tr><tr><td>Other miscellaneous</td><td>10%</td></tr><tr><td>Other punctual applications</td><td>7%</td></tr><tr><td>Pharmaceutics & cosmetics</td><td>10%</td></tr><tr><td>Transport</td><td>25%</td></tr></table> | Agricultural & environmental applications | 5% | Alloys & solders | 28% | Catalysts (homogenous & aggressive env.) | 5% | Other industrial, military & energy applications | 10% | Other miscellaneous | 10% | Other punctual applications | 7% | Pharmaceutics & cosmetics | 10% | Transport | 25% | |
| Agricultural & environmental applications | 5% | | | | | | | | | | | | | | | | | |
| Alloys & solders | 28% | | | | | | | | | | | | | | | | | |
| Catalysts (homogenous & aggressive env.) | 5% | | | | | | | | | | | | | | | | | |
| Other industrial, military & energy applications | 10% | | | | | | | | | | | | | | | | | |
| Other miscellaneous | 10% | | | | | | | | | | | | | | | | | |
| Other punctual applications | 7% | | | | | | | | | | | | | | | | | |
| Pharmaceutics & cosmetics | 10% | | | | | | | | | | | | | | | | | |
| Transport | 25% | | | | | | | | | | | | | | | | | |
| Production yield | Most bismuth is obtained as a by-product of lead, while the remainder is obtained as a by-product from various non-ferrous ores, and as a primary product from bismuth-bearing sulfide ores in two mines (one in Bolivia and one in China) (Raja, 2009; Singerling, 2020). According to Panousi et al. (2016), the Molybdenite Corporation of Canada reports that 70% to 80% of bismuth is recovered, based on which the authors estimated a recovery yield of 75%. The technical report for the NICO Gold-Cobalt-Bismuth-Copper Project in the Northwest Territories, Canada, estimates the production of 73 656 thousand pounds of refined bismuth for 102 082 thousand pounds extracted, suggesting a production yield of 72% (Burgess et al., 2014). Given the similarity between this value and the estimate from Panousi et al. (2016) and without further available data, the latter is considered as a reasonable estimate for the global production yield. | U1: 3 U2: 2 U3: 2 U4: 2 U5: 1 | | | | | | | | | | | | | | | | |
| Fabrication and manufacturing | 95% (assumption) | U1: 3 U2: 1 U3: 1 U4: 3 U5: 1 | | | | | | | | | | | | | | | | |
| New scrap recovery | 0%; new scrap recycling is considered to be included in the fabrication and manufacturing yield as home scrap recycling, if ever it occurs. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | | | |
| Remelting | N/A; 0% is reported in the dataset. | U1: 1 U2: 1 U3: 1 U4: 1 U5: 1 | | | | | | | | | | | | | | | | |
| Dissipation in use | Many bismuth uses are voluntarily dissipative as there are dissipated in use as a condition to obtain their function (type A dissipation), e.g. the use of bismuth subsalicylates as pharmaceuticals or animal feed, or dissipated during use due to the way they are used (type B dissipation), e.g. ammunition and fireworks. The end-use sectors that are considered to be 100% dissipative are pharmaceuticals & cosmetics, agricultural & environmental applications, and other punctual applications. No dissipation in use is reported for other sectors. | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | |
| Collection and sorting | Bismuth is not considered to be functionally recycled currently (European Commission, 2020a; Panousi et al., 2016). | Per sector; please refer to Supplementary Data | | | | | | | | | | | | | | | | |

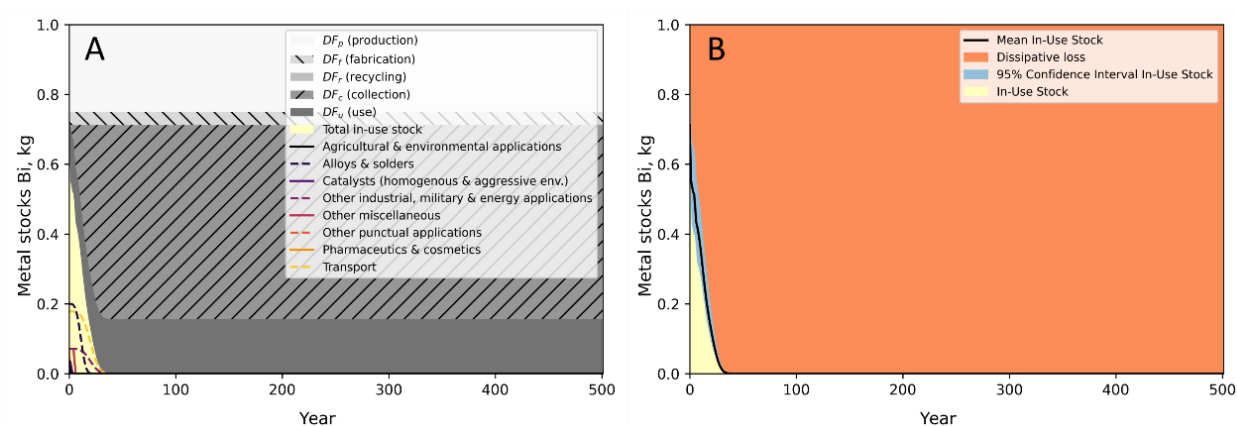


Figure B63. In-use stocks and losses of bismuth over 500 years. A: Detailed losses and in-use stock per sector. B: Uncertainty assessment.

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Annex C

This Annex provides the explanation of the calculation of Average Dissipation Rate (ADR) from ST_{TOT} .

We define the Average Dissipation Rate ADR as the inverse of the Total Service Time ST_{TOT} :

$$\frac{1}{ADR} = ST_{TOT} \Leftrightarrow ADR = \frac{1}{ST_{TOT}}$$

Likewise, the Total Service Time was calculated by the theoretically infinite integral (in practice sum over 1000 years) over the mass in service ratios $msr(t)$, which is a falling function of values between 0 and 1 with varying curvature which can only be calculated numerically.

$$ST_{TOT} = \int_0^{\infty} msr(t) dt = \sum_t msr(t) \cdot \Delta t$$

The rationale behind choosing the inverse of ST_{TOT} as the ADR is that we would get the same Total Service Time if the mass in service ratios were an exponential decay function with the ADR as the decay factor:

$$\int_0^{\infty} e^{-ADR \cdot t} dt = -\frac{1}{ADR} e^{-ADR \cdot t} \Big|_0^{\infty} = \frac{1}{ADR} = ST_{TOT}$$

For further discussion, let's assume such an exponential decay mass in service ratio:

$$msr(t) = e^{-ADR \cdot t}$$

In this case, the quotient between two consecutive mass in service ratios is always the same:

$$msr(t + \Delta t) = e^{-ADR \cdot \Delta t} \cdot msr(t) \Leftrightarrow \frac{msr(t + \Delta t)}{msr(t)} = e^{-ADR \cdot \Delta t} \approx 1 - ADR \cdot \Delta t$$

If $ADR = 0.009 \frac{\text{kg}}{\text{kg.yr}}$, then on average, the stock is diminishing every year through dissipation by about 0.9%.

Annex D

This annex provides midpoint (Table D1) and endpoint characterization factors (Table D2) for the ADR and LPST methods with their 95% confidence intervals, as computed with the Monte Carlo uncertainty propagation over 1,000 iterations.

Table D1. Midpoint characterization factors for the ADR and LPST methods and their 95% confidence intervals

| | LPST25 | LPST25 2.5 th centile | LPST25 97.5 th centile | LPST100 | LPST100 2.5 th centile | LPST100 97.5 th centile | LPST500 | LPST500 2.5 th centile | LPST500 97.5 th centile | ADR | ADR 2.5 th centile | ADR 97.5 th centile |
|-------|--------|--|---|---------|---|--|---------|---|--|--------|----------------------------------|-----------------------------------|
| 03_Li | 4.5E+0 | 3.7E+0 | 5.5E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.2E+1 | 1.4E+1 | 3.9E+1 |
| 04_Be | 1.9E+0 | 1.3E+0 | 2.7E+0 | 2.5E+0 | 2.0E+0 | 3.1E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 7.2E+0 | 4.8E+0 | 1.1E+1 |
| 05_B | 2.6E+0 | 1.8E+0 | 3.6E+0 | 2.4E+0 | 1.9E+0 | 3.0E+0 | 1.3E+0 | 1.2E+0 | 1.6E+0 | 6.3E+0 | 4.1E+0 | 1.0E+1 |
| 12_Mg | 5.0E+0 | 4.1E+0 | 6.0E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.0E+1 | 1.2E+1 | 3.7E+1 |
| 13_Al | 1.8E+0 | 1.3E+0 | 2.4E+0 | 1.6E+0 | 1.2E+0 | 2.0E+0 | 1.2E+0 | 1.1E+0 | 1.4E+0 | 2.0E+0 | 1.3E+0 | 3.4E+0 |
| 14_Si | 3.9E+0 | 3.1E+0 | 4.9E+0 | 2.9E+0 | 2.4E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.5E+1 | 9.9E+0 | 2.7E+1 |
| 21_Sc | 6.0E+0 | 5.1E+0 | 7.2E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 1.3E+4 | 4.0E+3 | 6.9E+5 |
| 22_Ti | 3.0E+0 | 2.3E+0 | 3.9E+0 | 2.8E+0 | 2.2E+0 | 3.4E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.2E+1 | 7.4E+0 | 1.9E+1 |
| 23_V | 4.8E+0 | 4.0E+0 | 6.0E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 2.0E+1 | 1.1E+1 | 4.0E+1 |
| 24_Cr | 2.3E+0 | 1.7E+0 | 3.1E+0 | 1.9E+0 | 1.5E+0 | 2.4E+0 | 1.3E+0 | 1.1E+0 | 1.5E+0 | 2.7E+0 | 1.6E+0 | 4.8E+0 |
| 25_Mn | 3.8E+0 | 3.0E+0 | 4.7E+0 | 2.6E+0 | 2.1E+0 | 3.2E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 8.3E+0 | 5.3E+0 | 1.4E+1 |
| 26_Fe | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 |
| 27_Co | 5.1E+0 | 4.3E+0 | 6.2E+0 | 3.1E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 3.8E+1 | 2.4E+1 | 6.5E+1 |
| 28_Ni | 2.0E+0 | 1.6E+0 | 2.7E+0 | 1.8E+0 | 1.5E+0 | 2.3E+0 | 1.2E+0 | 1.1E+0 | 1.5E+0 | 2.6E+0 | 1.7E+0 | 4.1E+0 |
| 29_Cu | 1.6E+0 | 1.2E+0 | 2.0E+0 | 1.9E+0 | 1.5E+0 | 2.3E+0 | 1.3E+0 | 1.1E+0 | 1.5E+0 | 3.4E+0 | 2.3E+0 | 5.1E+0 |
| 30_Zn | 2.7E+0 | 2.2E+0 | 3.4E+0 | 2.4E+0 | 2.0E+0 | 3.0E+0 | 1.3E+0 | 1.2E+0 | 1.6E+0 | 6.2E+0 | 4.1E+0 | 9.7E+0 |
| 31_Ga | 6.0E+0 | 5.1E+0 | 7.2E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 1.4E+3 | 4.2E+2 | 6.1E+4 |
| 32_Ge | 6.0E+0 | 5.1E+0 | 7.2E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 3.3E+3 | 8.5E+2 | 1.1E+5 |
| 33_As | 5.7E+0 | 4.8E+0 | 6.9E+0 | 3.1E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 8.2E+1 | 3.6E+1 | 3.2E+2 |
| 34_Se | 5.9E+0 | 5.0E+0 | 7.2E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.9E+2 | 9.4E+1 | 3.3E+3 |
| 38_Sr | 4.9E+0 | 4.0E+0 | 6.0E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.9E+1 | 1.5E+1 | 5.9E+1 |
| 39_Y | 4.9E+0 | 4.0E+0 | 6.0E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.7E+1 | 1.6E+1 | 5.0E+1 |

| | LPST25 | LPST25 2.5 th centile | LPST25 97.5 th centile | LPST100 | LPST100 2.5 th centile | LPST100 97.5 th centile | LPST500 | LPST500 2.5 th centile | LPST500 97.5 th centile | ADR | ADR 2.5 th centile | ADR 97.5 th centile |
|-------|--------|--|---|---------|---|--|---------|---|--|--------|----------------------------------|--------------------------------------|
| 40_Zr | 3.2E+0 | 2.5E+0 | 4.0E+0 | 2.7E+0 | 2.2E+0 | 3.3E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.0E+1 | 6.6E+0 | 1.6E+1 |
| 41_Nb | 2.7E+0 | 1.9E+0 | 3.7E+0 | 2.5E+0 | 2.0E+0 | 3.1E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 6.9E+0 | 4.5E+0 | 1.2E+1 |
| 42_Mo | 3.3E+0 | 2.6E+0 | 4.1E+0 | 2.4E+0 | 2.0E+0 | 3.1E+0 | 1.3E+0 | 1.2E+0 | 1.6E+0 | 6.3E+0 | 4.0E+0 | 1.1E+1 |
| 44_Ru | 3.5E+0 | 2.8E+0 | 4.3E+0 | 2.8E+0 | 2.2E+0 | 3.4E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.2E+1 | 7.2E+0 | 1.9E+1 |
| 45_Rh | 2.8E+0 | 2.2E+0 | 3.5E+0 | 2.5E+0 | 2.0E+0 | 3.0E+0 | 1.3E+0 | 1.2E+0 | 1.6E+0 | 6.5E+0 | 4.1E+0 | 1.0E+1 |
| 46_Pd | 2.5E+0 | 2.0E+0 | 3.2E+0 | 2.3E+0 | 1.9E+0 | 2.9E+0 | 1.3E+0 | 1.2E+0 | 1.6E+0 | 5.4E+0 | 3.4E+0 | 8.6E+0 |
| 47_Ag | 1.8E+0 | 1.3E+0 | 2.5E+0 | 2.0E+0 | 1.5E+0 | 2.5E+0 | 1.3E+0 | 1.1E+0 | 1.5E+0 | 3.5E+0 | 2.2E+0 | 5.6E+0 |
| 48_Cd | 4.2E+0 | 3.4E+0 | 5.2E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.8E+1 | 1.1E+1 | 3.0E+1 |
| 49_In | 5.7E+0 | 4.8E+0 | 6.9E+0 | 3.1E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 1.1E+2 | 5.1E+1 | 3.0E+2 |
| 50_Sn | 3.5E+0 | 2.9E+0 | 4.3E+0 | 2.8E+0 | 2.3E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.3E+1 | 8.2E+0 | 2.1E+1 |
| 51_Sb | 3.6E+0 | 3.0E+0 | 4.4E+0 | 2.8E+0 | 2.3E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.3E+1 | 8.4E+0 | 2.0E+1 |
| 52_Te | 5.9E+0 | 5.0E+0 | 7.1E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.4E+2 | 7.8E+1 | 3.2E+3 |
| 56_Ba | 5.4E+0 | 4.6E+0 | 6.5E+0 | 3.1E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 6.0E+1 | 3.7E+1 | 1.0E+2 |
| 57_La | 5.1E+0 | 4.3E+0 | 6.2E+0 | 3.1E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 3.8E+1 | 2.2E+1 | 6.9E+1 |
| 58_Ce | 4.8E+0 | 4.0E+0 | 6.0E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.7E+1 | 1.7E+1 | 5.2E+1 |
| 59_Pr | 4.6E+0 | 3.7E+0 | 5.6E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.4E+1 | 1.5E+1 | 4.2E+1 |
| 60_Nd | 4.2E+0 | 3.4E+0 | 5.3E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.0E+1 | 1.2E+1 | 3.5E+1 |
| 62_Sm | 3.5E+0 | 2.6E+0 | 4.6E+0 | 2.8E+0 | 2.3E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.4E+1 | 8.5E+0 | 2.5E+1 |
| 63_Eu | 5.4E+0 | 4.5E+0 | 6.5E+0 | 3.1E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 6.0E+1 | 3.6E+1 | 1.1E+2 |
| 64_Gd | 4.6E+0 | 3.8E+0 | 5.7E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.6E+1 | 1.5E+1 | 4.9E+1 |
| 65_Tb | 4.8E+0 | 3.9E+0 | 5.8E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 3.0E+1 | 1.8E+1 | 5.4E+1 |
| 66_Dy | 4.4E+0 | 3.7E+0 | 5.5E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.3E+1 | 1.4E+1 | 3.9E+1 |
| 67_Ho | 3.2E+0 | 2.0E+0 | 4.7E+0 | 2.8E+0 | 2.2E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.1E+1 | 6.7E+0 | 2.3E+1 |
| 68_Er | 3.3E+0 | 2.2E+0 | 4.7E+0 | 2.7E+0 | 2.2E+0 | 3.4E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.1E+1 | 6.5E+0 | 2.1E+1 |
| 69_Tm | 4.5E+0 | 3.4E+0 | 5.7E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.3E+1 | 1.3E+1 | 5.0E+1 |
| 70_Yb | 4.5E+0 | 3.4E+0 | 5.7E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.3E+1 | 1.3E+1 | 5.2E+1 |
| 71_Lu | 4.8E+0 | 3.7E+0 | 6.1E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 2.6E+1 | 1.4E+1 | 7.0E+1 |
| 72_Hf | 6.0E+0 | 5.1E+0 | 7.2E+0 | 3.2E+0 | 2.6E+0 | 3.9E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 2.1E+3 | 5.3E+2 | 9.1E+4 |
| 73-Ta | 4.0E+0 | 3.3E+0 | 4.9E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.7E+1 | 1.1E+1 | 2.6E+1 |
| 74_W | 4.7E+0 | 3.9E+0 | 5.6E+0 | 3.0E+0 | 2.5E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.7E+1 | 1.8E+1 | 4.2E+1 |
| 75_Re | 4.0E+0 | 3.3E+0 | 5.0E+0 | 2.9E+0 | 2.3E+0 | 3.5E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.5E+1 | 9.4E+0 | 2.5E+1 |
| 76_Os | 5.2E+0 | 4.3E+0 | 6.3E+0 | 3.1E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 4.3E+1 | 2.6E+1 | 7.9E+1 |

| | LPST25 | LPST25 2.5 th centile | LPST25 97.5 th centile | LPST100 | LPST100 2.5 th centile | LPST100 97.5 th centile | LPST500 | LPST500 2.5 th centile | LPST500 97.5 th centile | ADR | ADR 2.5 th centile | ADR 97.5 th centile |
|--------------|--------|--|---|---------|---|--|---------|---|--|--------|----------------------------------|--------------------------------------|
| 77_Ir | 4.1E+0 | 3.3E+0 | 5.0E+0 | 2.9E+0 | 2.4E+0 | 3.6E+0 | 1.4E+0 | 1.2E+0 | 1.6E+0 | 1.6E+1 | 1.0E+1 | 2.7E+1 |
| 78_Pt | 2.6E+0 | 2.1E+0 | 3.3E+0 | 2.1E+0 | 1.7E+0 | 2.7E+0 | 1.3E+0 | 1.2E+0 | 1.5E+0 | 3.8E+0 | 2.3E+0 | 6.2E+0 |
| 79_Au | 1.8E+0 | 1.2E+0 | 2.7E+0 | 1.2E+0 | 8.5E-1 | 1.7E+0 | 9.4E-1 | 7.0E-1 | 1.2E+0 | 8.0E-1 | 4.0E-1 | 1.7E+0 |
| 80_Hg | 5.0E+0 | 4.2E+0 | 6.1E+0 | 3.0E+0 | 2.5E+0 | 3.8E+0 | 1.4E+0 | 1.3E+0 | 1.7E+0 | 3.6E+1 | 2.2E+1 | 6.2E+1 |
| 81_Tl | 4.4E+0 | 3.6E+0 | 5.3E+0 | 3.0E+0 | 2.4E+0 | 3.7E+0 | 1.4E+0 | 1.2E+0 | 1.7E+0 | 2.2E+1 | 1.4E+1 | 3.7E+1 |

Table D2. Endpoint characterization factors for the ADR and LPST methods and their 95% confidence intervals

| | LPST25 | LPST25 2.5 th centile | LPST25 97.5 th centile | LPST100 | LPST100 2.5 th centile | LPST100 97.5 th centile | LPST500 | LPST500 2.5 th centile | LPST500 97.5 th centile | ADR | ADR 2.5 th centile | ADR 97.5 th centile |
|-------|--------|--|---|---------|---|--|---------|---|--|--------|----------------------------------|--------------------------------------|
| 03_Li | 2.2E+1 | 1.8E+1 | 2.7E+1 | 1.5E+1 | 1.2E+1 | 1.8E+1 | 6.9E+0 | 6.2E+0 | 8.2E+0 | 1.1E+2 | 6.7E+1 | 1.9E+2 |
| 04_Be | 9.3E+2 | 6.6E+2 | 1.3E+3 | 1.2E+3 | 1.0E+3 | 1.6E+3 | 6.7E+2 | 6.0E+2 | 8.0E+2 | 3.6E+3 | 2.4E+3 | 5.7E+3 |
| 05_B | 2.5E+0 | 1.8E+0 | 3.5E+0 | 2.3E+0 | 1.9E+0 | 2.9E+0 | 1.3E+0 | 1.2E+0 | 1.5E+0 | 6.0E+0 | 3.9E+0 | 9.9E+0 |
| 12_Mg | 3.4E+0 | 2.8E+0 | 4.1E+0 | 2.0E+0 | 1.6E+0 | 2.5E+0 | 9.4E-1 | 8.4E-1 | 1.1E+0 | 1.4E+1 | 8.0E+0 | 2.5E+1 |
| 13_Al | 5.1E+0 | 3.6E+0 | 6.8E+0 | 4.5E+0 | 3.4E+0 | 5.8E+0 | 3.4E+0 | 3.0E+0 | 4.1E+0 | 5.8E+0 | 3.6E+0 | 9.8E+0 |
| 14_Si | 1.1E+1 | 8.5E+0 | 1.3E+1 | 7.9E+0 | 6.5E+0 | 9.8E+0 | 3.8E+0 | 3.4E+0 | 4.5E+0 | 4.2E+1 | 2.7E+1 | 7.3E+1 |
| 21_Sc | 5.3E+4 | 4.5E+4 | 6.3E+4 | 2.8E+4 | 2.3E+4 | 3.4E+4 | 1.2E+4 | 1.1E+4 | 1.5E+4 | 1.2E+8 | 3.5E+7 | 6.0E+9 |
| 22_Ti | 4.5E+1 | 3.5E+1 | 5.9E+1 | 4.2E+1 | 3.4E+1 | 5.1E+1 | 2.1E+1 | 1.9E+1 | 2.5E+1 | 1.7E+2 | 1.1E+2 | 2.8E+2 |
| 23_V | 1.6E+2 | 1.3E+2 | 2.0E+2 | 9.9E+1 | 8.1E+1 | 1.2E+2 | 4.7E+1 | 4.2E+1 | 5.5E+1 | 6.7E+2 | 3.7E+2 | 1.4E+3 |
| 24_Cr | 6.8E+0 | 5.0E+0 | 8.9E+0 | 5.5E+0 | 4.2E+0 | 7.1E+0 | 3.7E+0 | 3.2E+0 | 4.3E+0 | 7.9E+0 | 4.8E+0 | 1.4E+1 |
| 25_Mn | 6.6E+0 | 5.3E+0 | 8.2E+0 | 4.6E+0 | 3.7E+0 | 5.7E+0 | 2.4E+0 | 2.1E+0 | 2.8E+0 | 1.5E+1 | 9.3E+0 | 2.4E+1 |
| 26_Fe | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 | 1.0E+0 |
| 27_Co | 2.4E+2 | 2.0E+2 | 2.9E+2 | 1.4E+2 | 1.2E+2 | 1.8E+2 | 6.6E+1 | 5.9E+1 | 7.9E+1 | 1.8E+3 | 1.1E+3 | 3.1E+3 |
| 28_Ni | 5.2E+1 | 3.9E+1 | 6.7E+1 | 4.6E+1 | 3.7E+1 | 5.7E+1 | 3.1E+1 | 2.8E+1 | 3.7E+1 | 6.6E+1 | 4.4E+1 | 1.0E+2 |
| 29_Cu | 1.4E+1 | 1.0E+1 | 1.8E+1 | 1.7E+1 | 1.3E+1 | 2.0E+1 | 1.1E+1 | 1.0E+1 | 1.3E+1 | 3.0E+1 | 2.0E+1 | 4.4E+1 |
| 30_Zn | 7.9E+0 | 6.4E+0 | 9.9E+0 | 7.1E+0 | 5.8E+0 | 8.8E+0 | 4.0E+0 | 3.5E+0 | 4.7E+0 | 1.8E+1 | 1.2E+1 | 2.9E+1 |
| 31_Ga | 3.7E+3 | 3.1E+3 | 4.4E+3 | 2.0E+3 | 1.6E+3 | 2.4E+3 | 8.7E+2 | 7.8E+2 | 1.0E+3 | 8.5E+5 | 2.6E+5 | 3.7E+7 |
| 32_Ge | 1.0E+4 | 8.6E+3 | 1.2E+4 | 5.4E+3 | 4.4E+3 | 6.6E+3 | 2.4E+3 | 2.1E+3 | 2.8E+3 | 5.6E+6 | 1.4E+6 | 1.9E+8 |
| 33_As | 4.5E+0 | 3.8E+0 | 5.4E+0 | 2.5E+0 | 2.0E+0 | 3.1E+0 | 1.1E+0 | 1.0E+0 | 1.3E+0 | 6.5E+1 | 2.8E+1 | 2.5E+2 |
| 34_Se | 5.7E+2 | 4.8E+2 | 6.9E+2 | 3.0E+2 | 2.5E+2 | 3.7E+2 | 1.4E+2 | 1.2E+2 | 1.6E+2 | 2.8E+4 | 9.0E+3 | 3.1E+5 |
| 38_Sr | 5.6E+0 | 4.6E+0 | 6.8E+0 | 3.4E+0 | 2.8E+0 | 4.2E+0 | 1.6E+0 | 1.4E+0 | 1.9E+0 | 3.3E+1 | 1.8E+1 | 6.7E+1 |
| 39_Y | 1.8E+2 | 1.5E+2 | 2.3E+2 | 1.1E+2 | 9.3E+1 | 1.4E+2 | 5.3E+1 | 4.7E+1 | 6.3E+1 | 1.0E+3 | 5.9E+2 | 1.9E+3 |
| 40_Zr | 4.8E+0 | 3.8E+0 | 6.0E+0 | 4.0E+0 | 3.3E+0 | 5.0E+0 | 2.1E+0 | 1.8E+0 | 2.4E+0 | 1.5E+1 | 1.0E+1 | 2.4E+1 |
| 41_Nb | 7.7E+1 | 5.3E+1 | 1.1E+2 | 7.1E+1 | 5.7E+1 | 8.9E+1 | 3.9E+1 | 3.5E+1 | 4.6E+1 | 2.0E+2 | 1.3E+2 | 3.3E+2 |
| 42_Mo | 1.5E+2 | 1.2E+2 | 1.9E+2 | 1.1E+2 | 9.1E+1 | 1.4E+2 | 6.2E+1 | 5.6E+1 | 7.3E+1 | 2.9E+2 | 1.9E+2 | 4.9E+2 |
| 44_Ru | 1.9E+4 | 1.5E+4 | 2.3E+4 | 1.5E+4 | 1.2E+4 | 1.8E+4 | 7.4E+3 | 6.6E+3 | 8.8E+3 | 6.3E+4 | 3.9E+4 | 1.0E+5 |
| 45_Rh | 2.2E+5 | 1.7E+5 | 2.7E+5 | 1.9E+5 | 1.5E+5 | 2.4E+5 | 1.1E+5 | 9.4E+4 | 1.2E+5 | 5.1E+5 | 3.2E+5 | 8.1E+5 |
| 46_Pd | 4.5E+4 | 3.5E+4 | 5.7E+4 | 4.1E+4 | 3.3E+4 | 5.2E+4 | 2.4E+4 | 2.1E+4 | 2.8E+4 | 9.6E+4 | 6.0E+4 | 1.5E+5 |
| 47_Ag | 1.4E+3 | 1.0E+3 | 1.9E+3 | 1.5E+3 | 1.2E+3 | 1.9E+3 | 1.0E+3 | 8.9E+2 | 1.2E+3 | 2.7E+3 | 1.7E+3 | 4.4E+3 |
| 48_Cd | 1.8E+1 | 1.4E+1 | 2.2E+1 | 1.2E+1 | 9.9E+0 | 1.5E+1 | 5.8E+0 | 5.2E+0 | 6.9E+0 | 7.6E+1 | 4.8E+1 | 1.2E+2 |

| | LPST25 | LPST25 2.5 th centile | LPST25 97.5 th centile | LPST100 | LPST100 2.5 th centile | LPST100 97.5 th centile | LPST500 | LPST500 2.5 th centile | LPST500 97.5 th centile | ADR | ADR 2.5 th centile | ADR 97.5 th centile |
|-------|--------|--|---|---------|---|--|---------|---|--|--------|----------------------------------|--------------------------------------|
| 49_In | 4.2E+3 | 3.5E+3 | 5.0E+3 | 2.3E+3 | 1.9E+3 | 2.8E+3 | 1.0E+3 | 9.2E+2 | 1.2E+3 | 7.8E+4 | 3.7E+4 | 2.2E+5 |
| 50_Sn | 9.8E+1 | 8.0E+1 | 1.2E+2 | 7.8E+1 | 6.4E+1 | 9.6E+1 | 3.8E+1 | 3.4E+1 | 4.5E+1 | 3.6E+2 | 2.3E+2 | 5.7E+2 |
| 51_Sb | 3.7E+1 | 3.0E+1 | 4.5E+1 | 2.9E+1 | 2.3E+1 | 3.6E+1 | 1.4E+1 | 1.3E+1 | 1.7E+1 | 1.3E+2 | 8.6E+1 | 2.1E+2 |
| 52_Te | 1.1E+3 | 9.5E+2 | 1.4E+3 | 6.1E+2 | 5.0E+2 | 7.5E+2 | 2.7E+2 | 2.4E+2 | 3.2E+2 | 4.7E+4 | 1.5E+4 | 6.0E+5 |
| 56_Ba | 6.6E-1 | 5.5E-1 | 7.9E-1 | 3.8E-1 | 3.1E-1 | 4.6E-1 | 1.7E-1 | 1.5E-1 | 2.0E-1 | 7.2E+0 | 4.5E+0 | 1.2E+1 |
| 57_La | 3.3E+1 | 2.7E+1 | 3.9E+1 | 1.9E+1 | 1.6E+1 | 2.4E+1 | 8.9E+0 | 8.0E+0 | 1.1E+1 | 2.4E+2 | 1.4E+2 | 4.4E+2 |
| 58_Ce | 3.1E+1 | 2.6E+1 | 3.8E+1 | 1.9E+1 | 1.6E+1 | 2.4E+1 | 9.0E+0 | 8.1E+0 | 1.1E+1 | 1.8E+2 | 1.1E+2 | 3.3E+2 |
| 59_Pr | 4.6E+2 | 3.7E+2 | 5.7E+2 | 3.0E+2 | 2.5E+2 | 3.7E+2 | 1.4E+2 | 1.3E+2 | 1.7E+2 | 2.4E+3 | 1.5E+3 | 4.2E+3 |
| 60_Nd | 2.8E+2 | 2.3E+2 | 3.5E+2 | 1.9E+2 | 1.6E+2 | 2.4E+2 | 9.2E+1 | 8.2E+1 | 1.1E+2 | 1.3E+3 | 8.1E+2 | 2.3E+3 |
| 62_Sm | 5.6E+1 | 4.1E+1 | 7.3E+1 | 4.5E+1 | 3.7E+1 | 5.6E+1 | 2.2E+1 | 2.0E+1 | 2.6E+1 | 2.2E+2 | 1.4E+2 | 3.9E+2 |
| 63_Eu | 1.7E+3 | 1.4E+3 | 2.0E+3 | 9.7E+2 | 7.9E+2 | 1.2E+3 | 4.4E+2 | 3.9E+2 | 5.2E+2 | 1.9E+4 | 1.1E+4 | 3.6E+4 |
| 64_Gd | 2.2E+2 | 1.8E+2 | 2.7E+2 | 1.4E+2 | 1.2E+2 | 1.8E+2 | 6.6E+1 | 5.9E+1 | 7.9E+1 | 1.2E+3 | 7.1E+2 | 2.3E+3 |
| 65_Tb | 3.5E+3 | 2.9E+3 | 4.3E+3 | 2.2E+3 | 1.8E+3 | 2.7E+3 | 1.0E+3 | 9.1E+2 | 1.2E+3 | 2.2E+4 | 1.3E+4 | 4.0E+4 |
| 66_Dy | 1.4E+3 | 1.1E+3 | 1.7E+3 | 9.3E+2 | 7.7E+2 | 1.2E+3 | 4.4E+2 | 3.9E+2 | 5.2E+2 | 7.1E+3 | 4.5E+3 | 1.2E+4 |
| 67_Ho | 3.0E+2 | 1.9E+2 | 4.4E+2 | 2.6E+2 | 2.1E+2 | 3.2E+2 | 1.3E+2 | 1.1E+2 | 1.5E+2 | 1.1E+3 | 6.3E+2 | 2.1E+3 |
| 68_Er | 1.4E+2 | 9.3E+1 | 2.0E+2 | 1.2E+2 | 9.4E+1 | 1.4E+2 | 5.8E+1 | 5.2E+1 | 6.9E+1 | 4.5E+2 | 2.8E+2 | 8.9E+2 |
| 69_Tm | 1.4E+3 | 1.1E+3 | 1.8E+3 | 9.3E+2 | 7.6E+2 | 1.2E+3 | 4.4E+2 | 3.9E+2 | 5.2E+2 | 7.3E+3 | 4.0E+3 | 1.6E+4 |
| 70_Yb | 3.3E+2 | 2.5E+2 | 4.3E+2 | 2.2E+2 | 1.8E+2 | 2.7E+2 | 1.0E+2 | 9.2E+1 | 1.2E+2 | 1.7E+3 | 9.4E+2 | 3.8E+3 |
| 71_Lu | 8.6E+3 | 6.6E+3 | 1.1E+4 | 5.3E+3 | 4.4E+3 | 6.6E+3 | 2.5E+3 | 2.2E+3 | 2.9E+3 | 4.7E+4 | 2.4E+4 | 1.2E+5 |
| 72_Hf | 3.2E+3 | 2.7E+3 | 3.9E+3 | 1.7E+3 | 1.4E+3 | 2.1E+3 | 7.6E+2 | 6.8E+2 | 9.0E+2 | 1.1E+6 | 2.8E+5 | 4.9E+7 |
| 73-Ta | 9.7E+2 | 8.1E+2 | 1.2E+3 | 7.0E+2 | 5.7E+2 | 8.6E+2 | 3.3E+2 | 3.0E+2 | 4.0E+2 | 4.0E+3 | 2.6E+3 | 6.2E+3 |
| 74_W | 2.2E+2 | 1.9E+2 | 2.7E+2 | 1.4E+2 | 1.2E+2 | 1.8E+2 | 6.7E+1 | 6.0E+1 | 7.9E+1 | 1.3E+3 | 8.4E+2 | 2.0E+3 |
| 75_Re | 2.2E+4 | 1.8E+4 | 2.7E+4 | 1.5E+4 | 1.3E+4 | 1.9E+4 | 7.5E+3 | 6.6E+3 | 8.8E+3 | 8.2E+4 | 5.0E+4 | 1.4E+5 |
| 76_Os | 1.7E+5 | 1.4E+5 | 2.1E+5 | 1.0E+5 | 8.2E+4 | 1.2E+5 | 4.6E+4 | 4.1E+4 | 5.4E+4 | 1.4E+6 | 8.5E+5 | 2.6E+6 |
| 77_Ir | 8.4E+4 | 6.8E+4 | 1.0E+5 | 5.9E+4 | 4.8E+4 | 7.3E+4 | 2.8E+4 | 2.5E+4 | 3.4E+4 | 3.3E+5 | 2.1E+5 | 5.4E+5 |
| 78_Pt | 1.1E+5 | 9.1E+4 | 1.4E+5 | 9.3E+4 | 7.5E+4 | 1.2E+5 | 5.7E+4 | 5.1E+4 | 6.8E+4 | 1.7E+5 | 1.0E+5 | 2.8E+5 |
| 79_Au | 8.1E+4 | 5.3E+4 | 1.2E+5 | 5.5E+4 | 3.8E+4 | 7.8E+4 | 4.2E+4 | 3.1E+4 | 5.4E+4 | 3.6E+4 | 1.8E+4 | 7.4E+4 |
| 80_Hg | 2.2E+2 | 1.9E+2 | 2.7E+2 | 1.3E+2 | 1.1E+2 | 1.7E+2 | 6.2E+1 | 5.5E+1 | 7.4E+1 | 1.6E+3 | 9.9E+2 | 2.8E+3 |
| 81_Tl | 3.2E+4 | 2.6E+4 | 3.9E+4 | 2.2E+4 | 1.8E+4 | 2.7E+4 | 1.0E+4 | 9.1E+3 | 1.2E+4 | 1.6E+5 | 1.0E+5 | 2.7E+5 |
| 82_Pb | 6.7E+0 | 4.3E+0 | 9.5E+0 | 6.8E+0 | 5.1E+0 | 8.6E+0 | 3.8E+0 | 3.4E+0 | 4.5E+0 | 1.6E+1 | 8.9E+0 | 2.9E+1 |
| 83_Bi | 1.1E+2 | 8.9E+1 | 1.4E+2 | 7.7E+1 | 6.3E+1 | 9.5E+1 | 3.7E+1 | 3.3E+1 | 4.3E+1 | 5.0E+2 | 3.2E+2 | 8.2E+2 |

Résumé étendu

Chapitre 1 : Introduction

La méthodologie d'analyse du cycle de vie (ACV), encadrée par les normes de l'Organisation internationale de normalisation (ISO) 14040/44 : 2006 (ISO, 2006a, 2006b), est une méthode d'évaluation d'impact environnementaux pertinente pour améliorer la conception des produits, communiquer sur leur performance environnementale, ainsi que soutenir l'élaboration des politiques publiques (Guinée et al., 2011). Les études ACV s'appuient sur une phase d'inventaire du cycle de vie et sur des méthodes d'évaluation d'impact environnementaux. Les flux de ressources extraites de l'environnement ainsi que les émissions vers l'environnement liées à un système défini, telles que compilées dans la phase d'inventaire, représentent l'ensemble des interactions entre l'environnement et la technosphère. En ACV, ces flux sont appelés flux élémentaires, et peuvent être caractérisés à l'aide de méthodes d'évaluation d'impact environnementaux (European Commission et al., 2010). Les impacts sont associés à différentes aires de protections : la santé humaine, les écosystèmes, et les ressources naturelles.

Différentes catégories de ressources existent, telles que l'eau, les ressources biotiques (bois, poissons, etc.), ainsi les ressources abiotiques fossiles et minérales. Dans cette thèse, nous nous intéressons particulièrement aux impacts de l'utilisation de ressources minérales sur l'aire de protection des ressources naturelles.

Les ressources minérales soutiennent les fonctions les plus indispensables dans les sociétés modernes (Graedel et al., 2013), par exemple l'agriculture, les infrastructures de haute technologie, les industries, la médecine et les transports. Au cours des dernières décennies, le nombre de substances exploitées par l'homme a explosé, de sorte que presque tous les éléments du tableau périodique sont désormais utilisés, dont plus de 60 métaux (Greenfield and Graedel, 2013). Ainsi, nous sommes aujourd'hui confrontés à un défi de taille : alors qu'une quantité croissante de minéraux est nécessaire pour soutenir les économies modernes, la pollution générée par leur exploitation et leur utilisation soulève des inquiétudes quant à la capacité de la terre à la supporter (Kesler and Simon, 2015; UNEP, 2016). Une meilleure gestion des ressources minérales permettrait d'optimiser la valeur socio-économique qu'elles génèrent pour la société, tout en contrôlant les impacts environnementaux associés. Ces dernières années, d'importantes mesures ont été mises en place pour améliorer la circularité et l'efficacité de l'utilisation des ressources (European Commission, 2018, 2020a; United Nations, 2018).

Les ressources minérales en ACV

Sonderegger et al. (2017) estiment que les ressources minérales devraient faire partie intégrante de l'aire de protection ressources naturelles, car elle proviennent de l'environnement naturel comme les autres ressources. Néanmoins, la prise en compte des ressources naturelles en tant qu'aire de protection en ACV a fait l'objet de discussions approfondies au cours des dernières années (Dewulf et al., 2015; Sonderegger et al., 2017; Sonnemann et al., 2015), avec une attention particulière portée sur la prise en compte des impacts liés à l'utilisation des ressources minérales (Berger et al., 2020; Drielsma et al., 2016b, 2016a; Schulze et al., 2020; Sonderegger et al., 2020). Environ 30 méthodes d'évaluation d'impact ont été développées pour traiter les impacts de l'utilisation des ressources minérales sur les aire de protection ressources naturelles. La plupart d'entre elles évaluent les effets de l'extraction de ressources minérales sur l'épuisement des réserves géologiques ou sur les efforts supplémentaires requis pour extraire davantage de ressources à l'avenir (Sonderegger et al., 2020).

Récemment, l'accessibilité des ressources minérales pour l'homme a été identifiée comme le problème clé à traiter pour cette aire de protection, couvrant à la fois les ressources primaires et secondaires (Schulze et al., 2020; van Oers et al., 2020). Le groupe de travail sur les ressources minérales de l'Initiative du Cycle de Vie du Programme des Nations Unies pour l'Environnement (PNUE) a proposé une définition consensuelle du sujet de sauvegarde des ressources minérales pour l'aire de protection : « le potentiel d'utiliser la valeur que les ressources minérales peuvent avoir pour l'homme dans la technosphère ». De plus, il a identifié le dommage causé à l'aire de protection comme « la réduction ou la perte de ce potentiel causé par l'activité humaine » (Berger et al., 2020; Sonderegger et al., 2020). Le groupe de travail a aussi regroupé les méthodes d'évaluation d'impact liés aux ressources minérale selon l'une des sept questions auxquelles elles répondent, par exemple « Comment puis-je quantifier la contribution d'un système de produit à l'épuisement des ressources minérales ? » (Berger et al., 2020).

De l'épuisement des ressources minérales à leur dissipation

Du point de vue socio-économique de l'aire de protection des ressources naturelles, les ressources sont généralement valorisées pour les fonctions qu'elles fournissent aux humains, c'est-à-dire leur valeur instrumentale (Frischknecht and Joliet, 2016; Sonderegger et al., 2017; Yellishetty et al., 2009). Les ressources peuvent également fournir d'autres valeurs menant au bien-être humain, telles que des valeurs économiques et culturelles (Ardenne et al., 2019). En ACV, les ressources extraites sont considérées comme les flux de l'ICV responsables de l'impact lié à l'utilisation des ressources minérales. Pourtant, puisque les ressources minérales (surtout, les métaux) sont indestructibles, les stocks globaux (stocks anthropiques et géologiques) restent inchangés sauf si les ressources ont été rendues inaccessibles par dissipation. Réduire les stocks géologiques peut inversement augmenter les

stocks en utilisation, ce qui peut être souhaitable du point de vue de l'utilité qu'ont les ressources pour l'homme. En effet, le sujet de sauvegarde défini par le groupe de travail du PNUE sur ressources minérales révèle que c'est la valeur des ressources dans la technosphère qui doit être protégée, plutôt que les stocks géologiques. Il est donc cohérent, comme le prévoit la Commission européenne, de passer d'un modèle d'évaluation des impacts caractérisant les flux extractifs, à un modèle caractérisant les flux dissipatifs de ressources minérales (European Commission, 2013; Zampori and Pant, 2019). Plusieurs travaux récents dans les communautés de l'ACV et de l'Analyse des Flux de Matière s'enlignent sur l'idée que les flux dissipatifs sont centraux à la problématique de gestion des ressources minérales (Berger et al., 2020; Gössling-Reisemann, 2008; Helbig et al., 2020; Schulze et al., 2020; Stewart and Weidema, 2005; Vadenbo et al., 2014; van Oers et al., 2002; van Oers and Guinée, 2016; Zampori and Sala, 2017; Zimmermann and Gößling-Reisemann, 2013, 2015).

Objectifs de la thèse

L'objectif de cette thèse est de fournir une méthode opérationnelle d'évaluation des impacts environnementaux pour prendre en compte les impacts de la dissipation des ressources minérales sur l'aire de protection des ressources naturelles. La méthode devrait être utilisable par les praticiens ACV souhaitant prendre en compte les impacts de la dissipation dans leurs études, en complément d'autres mécanismes d'impact concernant l'utilisation des ressources minérales. Par conséquent, la question centrale de cette thèse est la suivante :

"Peut-on développer des méthodes pour évaluer les impacts de la dissipation des ressources minérales sur l'aire de protection des ressources naturelles, de manière complémentaire aux autres méthodes d'évaluation d'impact existantes ?"

Les sous-objectifs suivants permettent de répondre à la question de recherche identifiée :

- a) Identifier les voies d'impact de l'utilisation des ressources minérales et leur lien avec le sujet de sauvegarde de l'aire de protection des ressources naturelles proposé par le groupe de travail du PNUE sur les ressources minérales de l'Initiative du Cycle de Vie.
- b) Identifier les défis pour prendre en compte la dissipation des ressources minérales et proposer un cadre conceptuel pour la considérer en ACV.
- c) Générer des données d'analyse de flux de matière dynamiques nécessaires pour développer des facteurs de caractérisation permettant de prendre en compte la dissipation des ressources minérales en ACV.
- d) Développer des méthodes d'évaluation de l'impact du cycle de vie et leurs facteurs de caractérisation respectifs pouvant être appliqués dans des études ACV.

e) Démontrer l'applicabilité des facteurs de caractérisation développés à l'aide d'une étude de cas.

Le cheminement de la thèse a permis de répondre aux sous-objectifs identifiés ci-dessus. Les chapitres 2 à 6 répondent chacun à un des sous-objectifs a) à e), et le chapitre 7 présente les conclusions. Les grandes lignes des développements réalisés dans chacun des chapitres sont exposées ci-dessous.

Chapitre 2. Etablissement des liens entre les chemins d'impact et les perspectives culturelles pour tenir compte des multiples aspects de l'utilisation des ressources minérales en analyse du cycle de vie

Le chapitre 2 fournit un contexte théorique dans lequel les voies d'impact et les méthodes d'évaluation d'impact associées peuvent être liées à l'aire de protection des ressources naturelles.

Malgré les avancées des dernières années (Dewulf et al., 2015; Drielsma et al., 2016b; Sonderegger et al., 2017), aborder les multiples aspects liés aux ressources minérales et structurer l'évaluation d'impact dans l'aire de protection reste un défi aujourd'hui. Bien que le groupe de travail sur les ressources minérales de l'Initiative du Cycle de Vie ait déterminé sept questions auxquelles les praticiens en ACV peuvent vouloir répondre, et recommandé des méthodes d'évaluation d'impact appropriées pour les traiter (Berger et al., 2020; Sonderegger et al., 2020), il n'a pas déterminé comment traiter les multiples aspects associés à l'utilisation des ressources minérales de façon concertée. De plus, la plupart des méthodes suggérées ou recommandées par ce groupe de travail quantifient les impacts midpoint plutôt que les dommages endpoint, ce qui suggère que l'identification et la mesure de ces dernières est compliquée. Un problème sous-jacent semble résider dans la définition des ressources, se référant systématiquement à leur valeur pour les humains, sans spécifier à quelle valeur, ni à quels humains il est fait référence. En outre, le sujet de sauvegarde connexe fait référence à leur accessibilité pour les humains globalement plutôt qu'à leur valeur intrinsèque dans l'environnement (Berger et al., 2020; Schulze et al., 2020). Or, si les ressources sont définies comme étant d'utilité ou de valeur pour l'homme en général, ou globalement, elles ne sont en fait bénéfiques qu'aux acteurs accédant et utilisant la valeur qu'elles ont pour leurs utilisateurs. Cela a été mis en évidence dans l'enthousiasme récent pour les évaluations de la criticité des matériaux (European Commission, 2020b; Graedel et al., 2015) et les méthodes d'évaluation basées sur le risque d'approvisionnement développées pour l'ACV (Bach et al., 2019; Cimprich et al., 2019; Gemechu et al., 2016).

Comme point de départ, il est donc pertinent de définir les ressources minérales dans un contexte d'approche cycle de vie, et d'identifier la valeur de ces ressources pour l'humain. Les ressources

minérales ont non seulement une valeur économique pour les organisations qui les extraient du sol et les vendent sur le marché, mais aussi une valeur d'usage une fois incorporée à des produits répondant à divers besoins humains. Ce sont ces deux valeurs qui peuvent être sujet de protection dans l'aire de protection telle que définie par le groupe de travail sur les ressources minérales (Berger et al., 2020).

Ensuite, les impacts potentiels liés à l'utilisation des ressources minérales peuvent être étudiés. Onze chemins d'impact ont été identifiés, en partie basés sur Berger et al. (2020):

- L'épuisement des réserves géologiques
- La sur-extraction actuelle des réserves géologique
- Les coûts supplémentaires de l'extraction future liée à l'extraction actuelle
- Un réinvestissement insuffisant des rentes liées à l'extraction
- Le risque d'approvisionnement global lié aux réserves géologiques (moyen-terme)
- La dissipation
- Le risque d'approvisionnement pour une entreprise (court-terme)
- La distribution non durable des ressources minérale vers différentes chaines de production
- Une création non durable de valeur économique dans les chaines de production
- Une distribution non durable des produits
- Une création non durable de valeur d'usage avec les produits manufacturés

Selon différentes perspectives culturelles, différentes stratégies de gestion des ressources minérales peuvent être proposées, car les personnes affiliées à ces perspectives poursuivent des objectifs socio-économiques différents. Par conséquent, différents aspects liés à l'utilisation des ressources minérales peuvent être les plus pertinents pour chacun d'entre elles. Ces chemins d'impacts doivent idéalement refléter les croyances de chacun des perspectives culturelles en terme de capacité d'adaptation des générations futures, des développements technologiques, etc.

Trois perspectives culturelles ont été considérées, telles que définies dans la Théorie Culturelle (Thompson et al., 1990) et étudiées dans le cadre de l'ACV par Hofstetter (1998) : les égalitaristes, les individualistes, et les hiérarchistes. Les égalitaristes valorisent le long terme sur le court terme et s'intéressent principalement à la survie globale et à long terme de la population humaine, avec une charge minimale transférée aux générations futures. Ils considèrent également les écosystèmes comme fragiles et sensibles aux interventions humaines, et pourraient donc soutenir que le maintien de leur intégrité est primordial pour soutenir la vie humaine à long terme car ils ne peuvent pas être remplacés. De plus, ils sont opposés au risque et considèrent les ressources comme sujettes à l'épuisement.

Les individualistes se positionnent devant les autres, à la fois dans l'espace et dans le temps. Ainsi, ils sont susceptibles de viser une rentabilité maximale pour la génération actuelle et localement. Ils sont optimistes quant aux évolutions technologiques et à la capacité d'adaptation des générations futures, et estiment que les ressources sont abondantes. Par conséquent, assurer le bien-être de l'organisation ou de la nation et maximiser ses profits à court ou à moyen terme semble être fondamental pour les individualistes.

Les hiérarchistes peuvent être considérés comme un juste milieu entre les perspectives égalitaire et individualiste. Ils favorisent un résultat juste et positif pour les générations actuelles et futures à l'échelle mondiale, et sont optimistes quant à l'adaptation technologique pour soutenir le bien-être humain. Par conséquent, on peut estimer que les hiérarchistes tenteraient de maintenir un équilibre entre le développement de la technosphère et la protection de l'environnement qui tendent à augmenter le bien-être humain à travers l'espace et le temps, c'est-à-dire en favorisant le développement des pays à faible revenu tout en maintenant le bien-être dans les pays industrialisés. Une telle stratégie de développement s'aligne généralement sur des principes de durabilité faible, qui contrastent avec une durabilité forte car elle favorise le progrès technologique comme moyen de développement humain et de bien-être, sur la base de l'hypothèse que le capital naturel peut essentiellement être remplacé par du capital manufacturé (Bullock, 2017; Ekins et al., 2003).

Suivant ces descriptions pour chaque perspective culturelle, les onze chemins d'impact identifiés peuvent être classifiés en fonction de la perspective ou des perspectives auxquels ils correspondent le mieux. Huit sont plus pertinents pour les égalitaristes, neuf pour les hiérarchistes, et trois pour les individualistes. Ces chemins sont liés à des dommages sur l'aire de protection des ressources naturelles, qui consiste en la possibilité de faire usage de la valeur des ressources minérales.

Chapitre 3. Dissipation des ressources minérales en analyse du cycle de vie : état de l'art et voies potentielles à suivre

Le chapitre 3 présente un état de l'art portant sur la dissipation des ressources minérales en ACV et identifie deux voies potentielles pour tenir compte de la dissipation des ressources minérales en ACV sur la base des résultats d'analyses de flux de matière dynamiques.

Les flux dissipatifs sont définis par Beylot et al. (2020) « des flux vers des puits ou des stocks qui ne sont pas accessibles aux utilisateurs futurs en raison de différentes contraintes. Ces contraintes empêchent l'homme d'exploiter la ou les fonctions que pourraient avoir les ressources dans la technosphère. La distinction entre les flux de ressources dissipatifs et non dissipatifs peut dépendre

de facteurs technologiques et économiques, qui peuvent changer avec le temps » (traduction libre depuis l'anglais). En fonction de cette définition, il est visible que les flux considérés comme dissipatifs doivent être des flux de ressources, et que l'horizon temporelle peut affecter quels flux sont considérés comme dissipatifs, comme l'évolution de critères économiques ou technologiques peuvent avoir une influence sur leur accessibilité future.

Différents acteurs peuvent avoir des définitions différentes de ressources. L'industrie minière définit les ressources minérales comme « une concentration ou une occurrence de matière solide d'intérêt économique dans ou sur la croûte terrestre sous une forme, une teneur ou une qualité et une quantité telles qu'il existe des perspectives raisonnables d'extraction économique éventuelle » (traduction libre de CRIRSCO, 2019). Les ressources minérales sont reclassées en réserves minérales si elles sont considérées actuellement économiquement exploitables, y compris les provisions pour pertes (CRIRSCO, 2019). Ainsi, les ressources minérales ne sont ciblées pour l'extraction que s'il est prospecté par l'industrie que la demande d'une ressource conduira à une rentabilité. Cette définition correspond à celle des ressources telles que comptabilisées dans les banques de données d'inventaire Gabi (Kupfer et al., 2020). Celle de la banque de données ecoinvent 3 (Wernet et al., 2016) s'y colle à la différence près qu'il est considéré que l'ensemble des métaux visés par les procédés d'extraction sont des ressources plutôt que seulement la fraction rentable économiquement.

En comparaison, la définition proposée par le groupe de travail sur les ressources minérales du PNUE suggère que tous les minéraux pouvant avoir une valeur pour l'être humain devraient être considérées comme des ressources (Berger et al., 2020). Selon cette définition ne spécifiant pas d'horizon temporelle, il est possible que tous les minéraux soient considérés comme des ressources naturelles s'ils sont nécessaires pour répondre aux besoins des générations actuelles et futures. Cette définition semble élargir le spectre de minéraux qui devraient être considérés comme des ressources au-delà de la définition court-termiste utilisée par les industries extractives et dans les banque de données d'inventaire.

De plus, puisque la problématique à traiter vis-à-vis des ressources minérales porte sur leur accessibilité, il est pertinent d'identifier les contraintes potentielles à faire usage de leur valeur avec une vision cycle de vie. Plusieurs contraintes ont été identifiées dans cet état de l'art :

Contraintes à l'utilisation des réserves géologiques :

- Exploration & découverte de gisements potentiellement viables
- Faisabilité technique et économique de l'exploitation minière
- Acceptabilité juridique, sociale et environnementale du projet minier

Contraintes à l'utilisation des ressources extraites/produites :

- Contraintes technico-économiques conduisant au stockage de ressources potentielles en tant que déchets ultimes ou non utilisés dans d'autres flux de matières
- Efficacité matérielle des procédés, y compris les émissions dans l'environnement et les déchets non recyclés (limitée par des défis techniques et économiques, par exemple le coût de l'énergie, les limites thermodynamiques, l'accessibilité aux ressources en eau et en énergie, etc.)
- Dissipation pendant l'utilisation (ex. : corrosion de barres d'acier)
- Comportement des consommateurs et de gestion des déchets (c.-à-d. collecte, tri et élimination inappropriés)
- Qualité (en termes, par exemple, de contamination ou de séparation des matériaux collectés) et/ou valeur des déchets collectés

En sus de l'état de l'art réalisé, deux options potentielle pour développer des approches permettant de considérer la dissipation de ressources minérales en ACV sont proposées. L'option 1 consiste à mettre à jour les ICV existants pour tenir compte des flux de dissipation et à appliquer des facteurs de caractérisation adaptés pour évaluer leurs impacts. L'option 2 consiste à développer des facteurs de caractérisation qui incluent des profils de dissipation pour différentes ressources minérales et à les appliquer directement aux flux d'extraction de ressources de l'ICV. L'option 2 sera mise en œuvre pour la suite de la thèse.

Chapitre 4. Durées de vie et pertes de métaux dans l'économie

Le chapitre 4 permet d'obtenir des résultats d'analyse de flux de matière dynamiques pour 61 métaux, en s'appuyant sur le modèle de dissipation MaTrace (Helbig et al., 2020; Nakamura et al., 2014). Il comprend une importante étape de collecte de données dans laquelle les rendements des processus et les distributions des utilisations finales sont compilés pour les 61 métaux étudiés. L'évaluation de l'incertitude est calculée pour l'ensemble de données et du modèle, ce qui permet de calculer un intervalle de confiance de 95% sur les résultats principaux. Un autre résultat de ce chapitre est une base de données transparente et lisible par machine, mis à la disposition du public sous le format ODYM, qui peut être réutilisé pour d'autres études dans les communautés de l'écologie industrielle ou de l'ACV.

Les pertes de 61 métaux ont été attribuées aux phases principales du cycle de vie : la production primaire, la fabrication, l'utilisation, la collecte des produits en fin de vie, et le recyclage. Les procédés de production ne ciblent souvent qu'un ou deux métaux en concentrations suffisantes dans les minerais extraits, laissant de côté les autres métaux car ils ne sont pas économiquement extractibles. Les pertes de production sont généralement plus faibles parmi les métaux produits en vrac, qui sont également des métaux porteurs dans la plupart des cas. Ils sont les plus importants pour 15 métaux, dont 13 sont des métaux spéciaux, les deux autres étant le vanadium et l'osmium. Environ 4 des 16 Mt de métaux spéciaux extraits sont directement détournés vers des installations d'élimination finale au cours de la production. Elles atteignent plus de 30 % des pertes totales pour les terres rares (série des lanthanides) et les métaux précieux, 50 % pour le cobalt, 70 % pour l'indium, et sont supérieures à 95 % pour l'arsenic, le gallium, le germanium, l'hafnium, le scandium, le sélénium, et le tellure. Les pertes de production sont proportionnellement plus faibles pour les métaux précieux, avec environ 6 sur 38 kt extraites, les métaux non ferreux, avec environ 20 sur 140 Mt extraits, et les métaux ferreux, avec environ 0,23 sur 1,8 Gt extraits. De cette dernière catégorie, le fer à lui seul représente environ 1,7 Gt extrait, dont 0,2 Gt sont perdus pour la production.

Les pertes cumulées dues aux procédés de fabrication sont les moins importantes pour 49 des 61 métaux. Ils sont négligeables pour le fer, et représentent moins de 1 % des pertes cumulées des métaux précieux (0,35 kt). Proportionnellement, ils deviennent plus importants parmi les métaux de spécialité avec 3 % de pertes cumulées (0,6 Mt), les métaux non ferreux (6 % de pertes, avec 9 Mt), et les métaux ferreux autres que le fer (7 % de pertes, avec 5 Mt dont 4 Mt de chrome). La plupart des métaux spéciaux subissent un cycle de vie unique, ce qui explique les pertes de fabrication et de fabrication plus faibles que les autres métaux.

Les pertes lors de la phase d'utilisation sont négligeables pour la plupart des métaux. Elles représentent environ 2 % des pertes pondérales totales pour les métaux ferreux (avec 30 Mt ; et 10 % hors fer, avec 7 Mt). De même, environ 2% des métaux précieux sont perdus lors de l'utilisation (700 tonnes). Les pertes d'usage sont plus importantes pour les métaux non ferreux (7 % des pertes, avec 10 Mt) et représentent jusqu'à 31% pour les métaux de spécialité (5 Mt). Ils sont plus importants pour quelques métaux volontairement utilisés dans des applications dissipatives. Des pertes généralement négligeables sont aussi dues à la dissipation involontaire lors de la phase d'utilisation, par exemple les pertes liées à la corrosion.

La majorité des pertes cumulées au fil du temps est due à la gestion et au recyclage des déchets. Ces pertes sont les plus importantes pour 43 métaux. La gestion et le recyclage des déchets représentent environ 85% des pertes de métaux ferreux (1,49 Gt dont 1,47 de fer), 80 % pour les métaux précieux

(31 kt), 71 % pour les métaux non ferreux (100 Mt) et 40 % pour les métaux spéciaux (6 Mt). Les métaux ayant de multiples cycles de vie grâce à des filières de collecte et de recyclage relativement efficaces sont malgré tout perdus lors de la gestion des déchets au fil du temps, bien que sur des périodes plus longues (par exemple, l'aluminium, le cuivre, l'or, le fer et le platine). Des pertes peuvent aussi avoir lieu pendant les procédés de recyclage, lors desquels certains métaux s'accumulent dans les poussières (par exemple, le zinc) et les scories (par exemple, le chrome et le vanadium) ou finissent comme contaminants dans les flux d'autres métaux (par exemple, le cuivre dans les flux d'acier) (Reck and Graedel, 2012; Reuter et al., 2019; UNEP, 2011).

A cause de ces pertes, les métaux étudiés présentent des profils très différents de dissipation au fil du temps. Nous avons estimé la durée de vie moyenne des métaux dans l'économie, à partir de l'extraction et jusqu'à leur perte totale. Ces durées de vie varient de moins d'un an (par exemple, pour le gallium et le sélénium) à un peu moins de deux siècles pour l'or. Généralement, les métaux ferreux (chrome, fer, manganèse, molybdène et nickel) et non ferreux (aluminium, cuivre, plomb, nickel et zinc), ainsi que les métaux précieux (or, palladium, rhodium, platine, argent), ont des durées de vie plus élevées. Ainsi, les durées de vie moyennes sont plus importantes parmi les métaux non ferreux (8 à 76 ans), les métaux précieux (4 à 192 ans) et les métaux ferreux (8 à 154 ans). En revanche, la durée de vie des métaux spéciaux varie de moins d'un an à 25 ans.

Chapitre 5. Méthodes d'évaluation des impacts du cycle de vie pour estimer les impacts des flux dissipatifs de métaux

Le chapitre 5 s'appuie sur la deuxième option présentée au chapitre 3, et propose deux méthodes permettant d'évaluer les impacts environnementaux dus aux flux dissipatifs des ressources minérales, qui peuvent être appliquées aux flux d'extraction dans l'ICV. La première méthode, appelée taux de dissipation moyen (ADR pour « average dissipation rate »), fournit des indications sur la vitesse à laquelle les différents métaux sont dissipés après avoir été extraits de l'environnement. Le second, appelé temps de service potentiel perdu (LPST pour « lost potential service time »), évalue la perte d'opportunité d'utiliser les ressources dissipées au fil du temps. Ces derniers sont mesurés pour trois horizons temporelles : 25, 100 et 500 ans. Ces facteurs de caractérisation « midpoint » sont calculés pour 61 métaux sur la base des résultats de l'analyse dynamique de flux de matière du Chapitre 4. De plus, des facteurs de caractérisation « endpoint » sont calculés en multipliant les facteurs midpoint avec un indice de prix pour les différents métaux.

Les facteurs de caractérisation midpoint pour la méthode ADR s'étalent sur 4 ordres de grandeur, avec 0,40-1,57 Fe-eq./kg pour l'or (Au) à 3 750-53 750 Fe-eq./kg pour le scandium (Sc). Les facteurs de caractérisation midpoint de la méthode ADR permettent une plus grande distinction entre les métaux. Ceux de la méthode LPST deviennent moins distinctifs sur un horizon temporel plus long. Par conséquent, peu ou pas de distinction peut être faite entre les facteurs de caractérisation midpoint pour les méthodes LPST100 (horizon temporelle de 100 ans) et LPST500 (500 ans) lorsque l'incertitude est prise en compte.

Des variations importantes peuvent être observées entre les facteurs de caractérisation midpoint et endpoint. Les métaux avec des profils de dissipation similaires, par exemple l'or et le fer, se différencient après l'application de l'indice des prix pour calculer les facteurs de caractérisation endpoint. Par exemple, en faisant abstraction de l'incertitude, le facteur de caractérisation midpoint de l'or est le plus bas des 61 métaux étudiés, car il est le mieux préservé dans l'économie; cependant, son indice de prix permettant de calculer le facteur endpoint multiplie le facteur midpoint par 44 621. Le facteur endpoint de l'or devient alors le 22^{ème} plus élevé des 61 métaux. De la même façon, le facteur endpoint du fer est multiplié par son indice de prix de 1, et reste parmi les plus petits facteurs de caractérisation, en troisième position après le baryum et le magnésium.

L'application de l'indice des prix pour calculer les CF de point final augmente la différenciation entre les facteurs de caractérisation d'ADR plus que ceux du LPST, car les facteurs midpoint d'ADR sont les plus différenciés au départ. Par exemple, la valeur moyenne des facteurs midpoint pour la méthode LPST100 ne varie que de 1 à 3,18, alors que ses facteurs endpoint s'étalent sur 5 ordres de grandeur. En comparaison, les facteurs midpoint et endpoint de la méthode ADR s'étalent sur 4 et 8 ordres de grandeur, respectivement. Par conséquent, on peut s'attendre à ce que les « hotspots » d'impacts soient les plus marqués en utilisant la méthode ADR endpoint.

Chapitre 6. Application de facteurs de caractérisation à 6 000 ensembles de données d'inventaire du cycle de vie

Le chapitre 6 présente une étude d'application des facteurs de caractérisation calculés pour les méthodes ADR et LPST. Pour cette évaluation, les flux élémentaires de 45 métaux sont caractérisés pour 5 999 ensembles de données de marché provenant d'une vaste base de données LCI, regroupés par section d'activité économique. Les résultats de l'évaluation d'impact sont comparés à ceux de modèles de caractérisation largement utilisés : la méthode du potentiel de déplétion abiotique (ADP) utilisant les réserves ultimes (van Oers et al., 2019, 2002) et la méthode ReCiPe 2016 (Huijbregts et al.,

2017). L'application des nouvelles méthodes démontre l'utilisabilité des méthodes LPST et ADR développées pendant cette thèse et les différences entre les scores d'impacts liés à la dissipation par rapport à ceux mesurés avec les autres méthodes.

La méthode ReCiPe 2016 dispose de facteurs de caractérisation pour 75 flux élémentaires de ressources minérales (dont l'uranium) dont 26 sont des composés minéraux ou des minerais. Certains de ces 26 derniers ne sont plus inclus dans la base de données ecoinvent version 3.7.1 (Wernet et al., 2016), car de nombreux composés minéraux ont été convertis en flux de métaux contenus depuis la version 3.6 (Moreno Ruiz et al., 2019). Les réserves ultimes d'ADP disposent de facteurs de caractérisation pour 75 éléments non énergétiques, couvrant les 61 éléments métalliques inclus dans les méthodes ADR et LPST. Seize de ces derniers métaux n'ont pas encore de flux de ressources correspondants dans ecoinvent version 3.7.1, et l'étude couvre donc les 45 métaux restants. La méthode ReCiPe 2016 n'inclue pas de facteurs de caractérisation pour le baryum et les terres rares, certaines desquelles sont couvertes dans cette étude. Les facteurs midpoint sont disponibles pour toutes les méthodes. La méthode ADP ne propose pas de facteurs de caractérisation endpoint.

Les résultats démontrent qu'il peut être attendu que différents métaux contribuent de façon importante aux impacts évalués par les différentes méthodes pour les différentes sections d'activité économique. Généralement, les impacts tels qu'évalués avec la méthode ADP font ressortir certains métaux précieux (l'or, le platine et le palladium) ainsi que le tellure et le cuivre comme ayant le plus d'impacts en terme de potentiel de déplétion des réserves géologiques. L'évaluation des impacts avec la méthode ReCiPe 2016 dévoilent que le fer, le nickel, l'or, le platine, le palladium et le cuivre contribuent fréquemment le plus aux impacts évalués par cette méthode : le surplus d'extraction future de minerais en midpoint, et le surplus de coûts futurs liés à ce surplus d'extraction en endpoint. Finalement, les impacts mesurés par les méthodes LPST et ADR midpoint et endpoint présentent des hotspots différents. En midpoint, le fer, le baryum et le zinc ressortent comme les principaux contributeurs aux impacts pour les deux méthodes, pour la plupart des sections d'activités économiques. En endpoint, le fer, le chrome, le nickel, l'or et le cuivre ressortent comme étant les plus impactants pour la méthode LPST ; et le fer, le nickel, le titane et le gallium ressortent comme les plus impactants pour la méthode ADR.

Ce cas d'étude réalisé sur un nombre important de données d'inventaire a permis de démontrer que les méthodes ADR et LPST peuvent être facilement utilisées dans les études ACV, fournissant des informations sur les profils de dissipation globale de différents métaux et sur les potentiels dommages socio-économiques de la dissipation pour les humains, tels que pris en compte dans l'aire de protection des ressources naturelles. Elle a aussi mis en avant le fait que différentes méthodes répondant à

différentes problématiques liées aux ressources minérales procurent des informations complémentaires qu'il pourrait être pertinent de considérer en ACV. Cependant, tel que discuté dans le chapitre 2, des efforts supplémentaires seront nécessaires pour évaluer les impacts des ressources minérales à l'aide de plusieurs méthodes d'évaluation des impacts de façon cohérente.

Chapitre 7. Discussion et conclusion

Dans ce chapitre, les méthodes ADR et LPST développées sont tout d'abord évaluées par rapport à cinq critères scientifiques, puis les voies à suivre pour une évaluation plus complète des impacts de l'utilisation des ressources minérales sur l'aire de protection des ressources naturelles sont discutées, et les perspectives pour l'évaluation de la dissipation des ressources minérales en ACV, y compris les perspectives pour les méthodes ADR et LPST, sont présentées. En outre, une conclusion générale montre comment les développements ont permis de répondre aux objectifs, et des perspectives pour la recherche future sont identifiées.

Les principaux résultats de cette thèse sont les facteurs de caractérisation permettant d'évaluer les impacts de la dissipation de ressources minérales, à travers l'utilisation des méthodes ADR et LPST. Les avancées proposées au fil des différents chapitres de la thèse ont permis d'atteindre les sous-objectifs identifiés au Chapitre 1, et de répondre favorablement à la question de recherche « **Peut-on développer des méthodes pour évaluer les impacts de la dissipation des ressources minérales sur l'aire de protection des ressources naturelles, de manière complémentaire aux autres méthodes d'évaluation d'impact ?** ».

Les résultats de cette thèse peuvent avoir des débouchés multiples. Dans le champ de recherche de l'ACV, le cadre théorique pour évaluer les impacts liés à différents aspects des ressources minérales (Chapitre 2) pourrait supporter des avancées théoriques et des développements de méthode d'évaluation des impacts complémentaires. Les méthodes d'évaluation d'impact de la dissipation des ressources minérales, ADR et LPST (Chapitre 5), pourraient être utilisées par des praticiens en ACV, tel que démontré au Chapitre 6. Ces méthodes pourraient être mises à jour régulièrement grâce au modèle et aux données compilées dans un format standardisé et lisible par une machine. L'appropriation de ces nouvelles méthodes et des résultats qu'elles mesurent par la communauté de l'ACV et les autres parties prenantes et décideurs sera déterminante pour leur utilisation future dans des études ACV.

De plus, des perspectives allant au-delà de la communauté ACV sont envisageables. Les taux de dissipation par métaux tels que représentés dans les facteurs de caractérisation d'ADR pourraient

servir comme indicateurs de circularité globaux. De plus, les données collectées pour l'étude d'analyse de flux de matière dynamique (Chapitre 4) pourraient servir de point de départ à d'autres études grande échelle dans la communauté de l'écologie industrielle.

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