Advancement of the LCA method to account for the dissipation of mineral resources and associated damage over the life cycle of products and systems : Validation of Acquired Experience (VAE)

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Par Antoine BEYLOT

Validation d'Acquis de l'Expérience (VAE) – Avancement de la méthode ACV pour la prise en compte de la dissipation des ressources minérales et du dommage associé, sur le cycle de vie des produits et systèmes

Validation of Acquired Experience (VAE) - Advancement of the LCA method to account for the dissipation of mineral resources and associated damage over the life cycle of products and systems

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Executive summary

Titre : Validation d'Acquis de l'Expérience (VAE) – Avancement de la méthode ACV pour la prise en compte de la dissipation des ressources minérales et du dommage associé, sur le cycle de vie des produits et systèmes

Résumé : Ce document correspond aux Parties 2 et 3 de mon dossier de candidature à la « Validation d'acquis de l'expérience, VAE, diplôme de doctorat » de l'Université de Bordeaux. Ces Parties 2 et 3 sont accessibles au public. La Partie 2 rend compte de « l'analyse des travaux, des méthodes et des résultats scientifiques d'une ou plusieurs recherches » que j'ai réalisées au cours de ma carrière de chercheur. Cette Partie porte sur l'avancement de la méthode d'Analyse du Cycle de Vie (ACV) auquel j'ai contribué à travers mes activités de recherche au Centre Commun de Recherche (CCR) de la Commission Européenne et au Bureau de Recherches Géologiques et Minières (BRGM), en vue de prendre en compte la dissipation des ressources minérales, et le dommage associé, induits tout au long du cycle de vie des produits et des systèmes. La Partie 3 (« Productions scientifiques ») rend compte de mes productions scientifiques au cours de mon parcours de recherche.

Les ressources minérales sont essentielles pour permettre à nos sociétés modernes de prospérer tout en atteignant les Objectifs de Développement Durable. L'impact induit par l'utilisation des ressources minérales au cours du cycle de vie d'un produit ou d'un système est abordé depuis longtemps en ACV, plus particulièrement au travers du concept de « déplétion des ressources ». À l'inverse, plus de 20 ans après que la « dissipation des ressources » a été mentionnée pour la première fois comme un concept potentiellement applicable pour évaluer l'impact sur les ressources naturelles en ACV, il n'y a jusqu'à présent pas eu de compréhension commune de ce concept, ni d'approche consensuelle pour l'aborder en ACV.

Cette Partie 2 de la VAE est divisée en 7 chapitres. Le premier chapitre introduit notamment l'objectif principal et les sous-objectifs de la recherche. Le chapitre 2 décrit ensuite le concept de dissipation des ressources tel que pris en compte dans la littérature, puis rend compte des principaux défis qui restent à relever pour appliquer ce concept en ACV - comme cela est ensuite exploré dans les chapitres suivants. Le chapitre 3 propose une nouvelle méthode (JRC-LCI) permettant de capter la dissipation des ressources au stade de l'Inventaire du Cycle de Vie (ICV). En particulier, ce chapitre détaille l'approche et sa mise en œuvre pratique dans les bases de données d'ICV, complétées d'une discussion autour de son application à un cas d'étude. Le chapitre 4 décrit par ailleurs une méthode d'évaluation d'impact (JRC-LCIA), dont le chemin d'impact et les facteurs de caractérisation associés permettent de quantifier le dommage induit par les flux dissipatifs. La combinaison de la méthode JRC, aux niveaux de l'ICV (JRC-LCI, Chapitre 3) et de l'évaluation du dommage (JRC-LCIA, Chapitre 4), permet ainsi de quantifier la réduction d'accès à la valeur des ressources minérales induite par un produit ou un système sur son cycle de vie. Le chapitre 4 décrit également, et discute, le test de cette méthode sur un cas d'étude. Le

chapitre 5 vise ensuite à étendre le test de la méthode JRC-LCI, en l'appliquant à 10 cas d'études de production primaire de matières premières minérales, ainsi qu'au cas du cycle de vie complet d'un produit (batterie lithium-ion de véhicules électriques). Plus généralement, le chapitre 5 vise i) à démontrer l'applicabilité de la méthode JRC-LCI, ii) à ouvrir la voie à une mise en œuvre de cette approche à plus grande échelle, dans l'ensemble des bases de données d'ICV, et iii) à discuter d'une potentielle amélioration de l'évaluation du dommage telle que développée au chapitre 4. Enfin le chapitre 6 analyse de manière critique les méthodes récemment développées et basées sur le concept de dissipation (ou d'accessibilité) des ressources minérales, dont les méthodes JRC-LCI et JRC-LCIA, en perspective avec la méthode de référence ADP, basée sur le concept de déplétion. Ce chapitre 6 décrit comment ces méthodes récentes, basées sur les concepts de dissipation et d'accessibilité, ont permis de faire progresser la prise en compte des impacts associés à l'utilisation des ressources minérales en ACV – tout en discutant de leurs limites et de leurs perspectives d'amélioration potentielle dans le futur. Le chapitre 7 prolonge cette discussion, ouvrant aux principales conclusions et perspectives de cette recherche.

Mots clés : VAE; ACV; ICV; ressources minérales; dissipation; indicateurs; dommages

Title: Validation of Acquired Experience (VAE) - Advancement of the LCA method to account for the dissipation of mineral resources and associated damage over the life cycle of products and systems

Abstract: This document stands for “Part 2” and “Part 3” of my application file for the validation of acquired experience to obtain the doctoral degree of the University of Bordeaux (in French “*Validation d’acquis de l’expérience, VAE, diplôme de doctorat*”). Part 2 and Part 3 are publicly available. Part 2 reports the “analysis of the work, methods and scientific results of one or more research” I carried out over my research career. It focuses on the advancement of the Life Cycle Assessment (LCA) method I contributed to through my research activities at the Joint Research Centre (JRC) of the European Commission (EC) and at the French Geological Survey (BRGM), with a view to accounting for the dissipation of mineral resources and associated damage induced over the life cycle of products and systems. Part 3 (“Scientific productions”) reports my scientific productions along my research career, in particular in terms of international publications in peer-reviewed journals, communications in international congresses with or without publication of proceedings, and scientific and technical reports.

Mineral resources are key to make our modern societies thrive while meeting Sustainable Development Goals. The impact induced by the use, or improper use, of mineral resources in a product or a system over its life cycle has long been addressed in LCA; in particular considering the concept of “resource depletion”. Oppositely, more than 20 years after “resource dissipation” was first mentioned as a concept potentially applicable to assess the impact on natural resources in LCA, there has been so far no common understanding of this concept neither a consensual approach to address it in LCA.

This Part 2 of the VAE is divided into 7 chapters. The first Chapter introduces the dissertation, in particular providing the research core objective and sub-objectives. Chapter 2 describes the status of resource dissipation in the literature, and then reports the key challenges that are still faced to enforce this concept in LCA. It finally paves the way towards implementation in LCA; as then explored in the following Chapters. Chapter 3 proposes a new method (the JRC-LCI method) to capture resource dissipation at the LCI stage, with accounting for dissipative resource flows. In particular, it details the approach and its practical operationalization in LCI databases, including application to a case study, and discussion. Chapter 4 moreover describes an impact assessment method (JRC-LCIA), including impact pathway and computation of characterization factors, which quantifies the damage induced by the dissipative flows captured through the JRC-LCI method. The combination of the JRC method, at the LCI level (JRC-LCI, Chapter 3) and at the impact assessment level (JRC-LCIA, Chapter 4), eventually enables to quantify the reduced accessibility to mineral resources value induced by a product or a system over its life cycle. Chapter 4 also describes the test of this method on a case study, and discusses these results. Chapter 5 aims at further testing the JRC-LCI method at the inventory level, by applying it to 10 cradle-to-gate case studies (primary production of raw materials) as well as one case study considering the full life cycle of a mineral raw material–based product (lithium-

ion battery for electric vehicles). More generally, Chapter 5 aims at i) demonstrating the applicability of the JRC-LCI method, ii) paving the way towards the upscaling of this approach, in whole LCI databases, and iii) discussing about potential refinement of the price-based impact assessment method as developed in Chapter 4. Chapter 6 finally critically analyses recent resource-dissipation (or -accessibility) based methods, including the JRC-LCI and JRC-LCIA methods and methods developed by other researchers in the meantime. It similarly reviews the ADP (depletion-based) method, which is the reference LCIA method in daily LCA practice. It describes how these recent resource-dissipation and -accessibility based methods (including the JRC methods) have enabled to advance the consideration of impacts associated with mineral resources use in LCA; and it eventually discusses their limits and perspectives for potential improvement in the future. Chapter 7 eventually concludes this dissertation, with describing the key findings of this research, and the main perspectives.

Keywords: VAE; LCA; LCI; mineral resources; dissipation; indicators; damages

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VAE - Partie 2 : Analyse du travail, des méthodes et des résultats scientifiques d'une ou plusieurs recherches déjà effectuées

et

Partie 3 : Productions scientifiques

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I first would like to thank the University of Bordeaux for giving me this remarkable opportunity to apply for the validation of acquired experience ("VAE") to obtain the doctoral degree.

I am moreover particularly grateful and thankful to my employer, the BRGM (the French Geological Survey), for supporting me in this application to the VAE. This support particularly consisted in offering me time to dedicate on this project, in addition to administrative support and funding of missions to Bordeaux. The BRGM has also offered me the opportunity to develop my research activities, from 2011 to 2017, and then from 2020-2023. In this document, Chapter 5, Chapter 6 and Chapter 7 in Part 2, and Part 3 ("Productions scientifiques") directly derive from, or reflect, research I performed at the BRGM. This document also partly benefited (in Chapter 6) from the financial support of ADEME in the context of the ERAMIN 2020 project PROPER (Contract n°2002C0079), and of SCORE LCA in the context of the study « Méthodes innovantes de comptabilisation des ressources en ACV » (Contract n°2020-05).

Moreover, I would like to thank the Joint Research Centre of the European Commission (EC-JRC) for giving me the opportunity to work on methods to address mineral resources use in LCA, in 2018-2019. Three of the articles I co-authored while at the JRC have now become, some years later and after slight redrafting, three Chapters of this document: Chapters 2 to 4, in Part 2. The associated studies (as per Chapters 2 to 4) have been financially supported by the Directorate General for the Environment (DG ENV) of the European Commission in the context of two Administrative Arrangements: Environmental Footprint and Material Efficiency (EFME 3) 33909 – 07.0201/2015/704456/SER/ENV.AI and Technical support for the Environmental Footprint and the Life Cycle Data Network (EF4) DG ENV N °070201/2019/811467/AA/ENV.B.1

Secondly, beyond the institutions, I am thankful to a number of people whose support has been essential in this journey. I first would like to thank my promotor Professor Guido Sonnemann (University of Bordeaux), for his valuable guidance and constructive advices. Regarding the University of Bordeaux, I am also very thankful to Professor Corine Mathonière (Head of the Doctoral School of Chemical Sciences) and Sandrine Riou (Administrative and educational manager VAE) for enabling me to apply to this VAE, and for their precious support along the way. Moreover I would like to warmly thank Jacques Villeneuve (Senior Engineer at BRGM) and Patrick d'Hugues (BRGM Head of the Mineral Resources and The Circular Economy Scientific Programme) for their continuous support right from my start at the BRGM, back in 2011. In this early stage of my research career, they identified the possibility for me to valorize my research efforts later through obtaining a PhD. And they continuously supported me in this direction all along the way. At the BRGM, I also would like to thank Philippe Freyssinet (Research and Innovation Director) and Nadine Gorin (Head of the Training Unit) for their support more specifically in this year, giving me this opportunity. I am moreover thankful to my former JRC colleagues (Fulvio Ardente, Scientific Officer; Luca Zampori, currently Senior Consultant at PRé Sustainability; and Serenella Sala, Head of the Land Resources and Supply Chain Assessments Unit) with who I collaborated in a number of topics – including the articles that have now become Chapters 2 to 4 of Part 2 of this document. Finally, I would like to thank all the co-authors of the articles I contributed to publish from 2013 to nowadays (as listed in Part 3), including in particular Frédéric Lai who first authored what has now become Chapter 5 in Part 2.

Finally, a heartfelt thanks to my close ones for their continuous and essential support.

Preface

This document stands for “Part 2” and “Part 3” of my application file for the validation of acquired experience to obtain the doctoral degree of the University of Bordeaux (in French “*Validation d’acquis de l’expérience, VAE, diplôme de doctorat*”). Part 2 and Part 3 are publicly available, while Part 1 (referred to below) is not. As requested in the application form:

- Part 2 reports the “*analysis of the work, methods and scientific results of one or more research*” I carried out over my research career. It focuses on the advancement of the Life Cycle Assessment method I contributed to through my research activities at the Joint Research Centre (JRC) of the European Commission (EC) and at the BRGM (the French Geological Survey) with a view to accounting for the dissipation of mineral resources and associated damages induced over the life cycle of products and systems.
- Part 3 (in this document, Chapter called “Scientific productions”) reports my scientific productions along my research career, in particular in terms of international publications in peer-reviewed journals, communications in international congresses with or without publication of proceedings, and scientific and technical reports.

This document (Part 2 and Part 3) complements Part 1, which is in particular made of two main chapters:

- Part 1A describes the main research activities I conducted over my career, from 2009 to my current activities at the BRGM nowadays. Part 1A moreover discusses the skills I developed over this period of time, and the consistency of my research activities;
- Part 1B describes three research missions I carried out over my research career, specifying for each mission: its nature (including the context, in particular the projects that supported this research), the associated tasks and work plan, and a synthesis of knowledge and skills developed and mobilized over these missions.

My full application file (in French “*dossier de demande de VAE*”) is made of Part 1 (including Parts 1A and 1B), Part 2 and Part 3. But only Part 2 and Part 3 (this document) are made publicly available.

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Acronyms and abbreviations

ADP: Abiotic Depletion Potential

ADR: Average Dissipation Rate

AoP: Area of Protection

ARP: Abiotic Resource Project

BRGM: Bureau de Recherches Géologiques et Minières

CF: Characterization Factor

EC: European Commission

EDP: Environmental Dissipation Potential

EF: Environmental Footprint

EoL: End-of-Life

GLAM: Global Guidance for Life Cycle Impact Assessment Indicators and Methods

IO: Input-Output

JRC: Joint Research Centre

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LiB: Lithium-ion Battery

LMO: Lithium Manganese Oxide

LPST: Lost Potential Service Time

MFA: Material Flow Analysis

OEF: Organization Environmental Footprint

PEF: Product Environmental Footprint

SFA: Substance Flow Analysis

TF: Task Force

UNEP: United Nations Environment Programme

USGS: United States Geological Survey

1 Chapter 1 - Introduction and research objectives

The major part of this Chapter 1, and in particular *Section 1.2 Research objectives* and *Section 1.3 Structure of this dissertation*, has been developed in the context of this VAE.

Moreover *Section 1.1 Impact induced by mineral resource use in LCA* builds on:

Beylot, A., Ardente, F., Sala, S., Zampori, L., 2020. Accounting for the dissipation of abiotic resources in LCA: Status, key challenges and potential way forward. Resources, Conservation and Recycling 157, 104748. https://doi.org/10.1016/j.resconrec.2020.104748

and

Beylot, A., Dewulf, J., Greffe, T., Muller, S., Blengini, G.-A. 2023. Mineral resources depletion, dissipation and accessibility in LCA: a critical analysis. Submitted to the International Journal of Life Cycle Assessment.

Contribution of the co-authors and acknowledgements are reported later in this document, as introduction to respectively Chapter 2 and Chapter 6.

1.1 Impact induced by mineral resource use in LCA

Mineral resources are key to make our modern societies thrive while meeting Sustainable Development Goals. The potential damage to current and future generations induced by the use, or improper use, of mineral resources in a product or a system over its life cycle has long been addressed in Life Cycle Assessment (LCA). Existing Life Cycle Impact Assessment (LCIA) methods have been classified in four categories according to their underlying impact mechanisms by the task force (TF) mineral resources of the United Nations Environment Programme (UNEP) Life Cycle Initiative, in the context of the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM2): depletion, future efforts, thermodynamic accounting, and supply risk methods (Sonderegger et al., 2020).

Methods related to the potential depletion of mineral resources address the reduction and subsequent potential exhaustion of a certain stock (of these mineral resources). They assume that the extraction of mineral resources from the ecosphere reduces the natural (geological) stock, making these resources less available (Sonderegger et al., 2020). Availability of a resource here concerns its physical presence (Schulze et al., 2020a). The abiotic depletion potential method (ADP, ultimate reserves; Guinée et al., 2002; van Oers et al., 2002) is in particular recommended in the GLAM2 context, for use by LCA practitioners interested in the relative contribution of a product system to the depletion of mineral resources and with a long term perspective (Berger et al., 2020). As a mirror to this set of recommendations from the UNEP Life Cycle Initiative, the European Commission (EC) similarly recommends the use of ADP characterization factors (CFs) in the context of the Product and Organization Environmental Footprint (PEF/OEF; Zampori and Pant, 2019; EC, 2021) when assessing impacts associated with mineral and metal resource use. Eventually the depletion-based ADP method has been and is extensively implemented in daily LCA practice, in particular thanks to adapted standard LCI databases (e.g. ecoinvent) and LCA software (e.g. SimaPro) that enable easy calculations.

However, abiotic resources may remain in the anthropogenic system, although transformed, and may be available for further uses. Accordingly, several authors (Yellishetty et al., 2011; Klinglmair et al., 2014; Frischknecht, 2014; Schneider et al., 2011 and 2015; and van Oers and Guinée, 2016) have discussed the possibility to consider also the amount of resources in the technosphere (e.g. in the form of scraps or waste) as part of the stocks potentially available in addition to geological stocks, and to include them in the calculation of characterization factors for assessing resource depletion. In parallel, as opposed to this concept of stocks of resources potentially available within the technosphere, the concept of resources or materials dissipation after their use in the technosphere has been increasingly considered in the fields of Substance and Material Flow Analysis (respectively SFA and MFA). Some authors have additionally called for considering this concept as well in LCA (Vadenbo et al., 2014), building on the foundations laid out by Stewart and Weidema (2005) and Heijungs et al. (1997). More recently, in the context of the Organisation Environmental Footprint Sector Rules (OEFSR) pilot, the need to move towards a dissipation concept has been highlighted, with a possible way forward as described in Annex V of the OEFSR on copper production (Zampori and Sala, 2017; Beylot et al., 2020b). The dissipation of resources was identified as a promising concept, whose feasibility for implementation in LCA has been further discussed (Zampori and Sala, 2017). Moreover, the TF mineral resources of the UNEP Life Cycle Initiative concludes its recommendations on the use of methods to assess the impact of mineral resource use with calling for the definition of the concept of dissipative resource use and for its integration in future method developments (Berger et al., 2020). To operationalize this concept in LCA, the Life Cycle Inventories (LCIs) need to provide information about dissipative losses or flows and LCIA methods need to be adapted or developed to account for the

impacts associated with these dissipative flows (Berger et al., 2020). However, more than 20 years after "resource dissipation" was first mentioned as potentially applicable to assess the impact on natural resources in LCA, there is currently no common understanding of this concept, and no synthesis on the studies that have used it so far (Lifset et al., 2012; Zimmermann, 2017).

1.2 Research objectives

As a core objective, this research aims at advancing the LCA method to account for the dissipation of mineral resources and associated damage over the life cycle of products and systems.

This needs the following sub-objectives to be achieved:

- SOa: to conceptualize resource dissipation in the context of Life Cycle Thinking, which in particular requires to provide a unique definition for this concept out of its diverse understandings in literature;
- SOb: to develop a method to capture mineral resource dissipation over the life cycle of products and systems, at the LCI stage;
- SOc: to develop an impact assessment method to capture the damage induced by dissipative flows of mineral resources over the life cycle of products and systems;
- SOd: to demonstrate the applicability of these methods and pave the way towards their implementation beyond the context of this research;
- SOe: to discuss how these new methods have advanced the consideration of impacts associated with mineral resources use in LCA, including limits and potential for improvement in the future, in perspective with other key methods, long standing or on the contrary recently developed.

1.3 Structure of this dissertation

Chapter 2 aims at i) describing the status of resource dissipation in the literature, in studies that trace the flows of materials from their extraction up to their end-of-life, and to provide one definition for this concept; ii) reporting the key challenges that are still faced to implement this concept in LCA; and iii) paving the way forward in the short-, mid- and long-terms for implementation in LCA; as then explored in the following Chapters.

Chapter 3 proposes a new method (the JRC-LCI method) to capture resource dissipation at the LCI stage, with accounting for dissipative resource flows. In particular, it details the approach and its practical operationalization in LCI databases. It moreover applies this new method to a case study (production of primary copper), and further discusses it considering three main angles: i) how it would change the interpretation of results regarding mineral resources in LCA, ii) how far some key methodological aspects of this approach (e.g. the temporal perspective) can affect the inventory results, and finally iii) the issue of new data requirements, in terms of availability and adequacy.

The JRC-LCI method enables to account for and distinguish between dissipative and non-dissipative resource flows at the unit process level, while not addressing the effect induced by these dissipative flows. Chapter 4 accordingly describes an impact assessment method (JRC-LCIA), including impact pathway and computation of characterization factors, which quantifies the damage induced by the

dissipative flows captured through the JRC-LCI method. The combination of the JRC method, at the LCI level (JRC-LCI, Chapter 3) and at the impact assessment level (JRC-LCIA, Chapter 4), eventually enables to quantify the reduced accessibility to mineral resources value induced by a product or a system over its life cycle. Chapter 4 also describes the test of this method on a case study, and discusses these results, in particular in terms of support to decision-making, sensitivity to the timeframe, and normalisation factor.

Chapter 5 aims at further testing the JRC-LCI method at the inventory level, by applying it to 10 cradle-to-gate case studies (primary production of raw materials) as well as one case study considering the full life cycle of a mineral raw material–based product (lithium-ion battery for electric vehicles). More generally, Chapter 5 aims at i) demonstrating the applicability of the JRC-LCI method as developed in Chapter 3, ii) paving the way towards the upscaling of this approach, in whole LCI databases, towards routine consideration of resource dissipation in LCA, and iii) discussing about potential refinement of the price-based impact assessment method as developed in Chapter 4, in particular with capturing the duration of inaccessibility.

Chapter 6 aims at critically analysing recent resource-dissipation (or -accessibility) based methods, including the JRC-LCI and JRC-LCIA methods and methods developed by other researchers in the meantime. It similarly reviews the ADP (depletion-based) method, which is the reference LCIA method in daily LCA practice. It describes the characteristics of these methods, and then performs an in-depth analysis including discussion on strengths and limits. It gives an overview of the methods' relevance to the safeguard subject, model robustness, data quality and completeness, and operational capabilities. It particularly discusses assumptions and modelling choices, including the scientific-evidence and scenarios on which they build. It describes how these recent resource-dissipation and -accessibility based methods (including the JRC methods) have enabled to advance the consideration of impacts associated with mineral resources use in LCA; and it eventually discusses their limits and perspectives for potential improvement in the future.

Finally Chapter 7 concludes this dissertation, with describing the key findings of this research, and the main perspectives.

2 Chapter 2 - Dissipation of abiotic resources in LCA: status, key challenges and potential way forward

This Chapter is essentially drawn from:

Beylot, A., Ardente, F., Sala, S., Zampori, L., 2020. Accounting for the dissipation of abiotic resources in LCA: Status, key challenges and potential way forward. Resources, Conservation and Recycling 157, 104748. https://doi.org/10.1016/j.resconrec.2020.104748

Contribution of the authors:

- Antoine Beylot: Conceptualization, Methodology, Formal analysis, Writing - original draft.
- Fulvio Ardente: Conceptualization, Methodology, Writing - review & editing.
- Serenella Sala: Conceptualization, Writing - review & editing, Supervision.
- Luca Zampori: Conceptualization, Methodology, Writing - review & editing.

2.1 Introduction

The dissipation of resources was identified as a promising concept, whose feasibility for implementation in LCA has been further discussed (Zampori and Sala, 2017). Moreover, the TF mineral resources of the UNEP Life Cycle Initiative also called for the consideration of dissipation in LCA, with effect on both inventories and impact assessment methods (Sonderegger et al., 2020; Berger et al., 2020). However, more than 20 years after "resource dissipation" was first mentioned as potentially applicable to assess the impact on natural resources in LCA, there is currently no common understanding of this concept, and no synthesis on the studies that have used it so far (Lifset et al., 2012; Zimmermann, 2017).

In this context, this Chapter aims at i) describing the status of resource dissipation in "life-cycle based studies" in the literature (that is, studies that trace the flows of materials from their extraction up to their end-of-life), and to provide a definition building from this review; ii) reporting the key challenges that are still faced to enforce this concept in LCA; and iii) discussing the potential way forward in the short-, mid- and long-terms for implementation in LCA. The two next sections (2.2 and 2.3) respectively review the concepts of "resources" and "resource dissipation", considering "resources" in their broad sense, i.e. in particular encompassing abiotic (fossil and mineral) resources, biotic resources, water, soil and land. Instead, sections 2.4 and 2.5 focus on the resources mostly addressed in the literature relative to resource dissipation, namely abiotic resources, to provide a definition for resource dissipation and to discuss both the key challenges it implies for implementation in LCA and the way forward. Even if limited to part of the resources only, these two sections are also intended to be a basis for potential generalization to other types of resources.

2.2 On the concept of "resources"

The term "resources" is used several times in ISO 14040 (ISO, 2006), which sets the principles and framework for LCA. In particular, the ISO standard states that "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle", yet without providing a definition for "resources". More generally, in many publications (in a broad sense; e.g. reports, communications, scientific articles), the concept of resource is taken for granted so that a clear definition is not provided. This is for example the case in the United Nations' milestone report on "Our Common Future", which includes the strategic imperative of "conserving and enhancing the resource base", overall pointing out that securing resources is a must for sustainable development, but without defining "resources" (UN, 1983).

In their discussion on mineral resources in LCIA, Drielsma et al. (2016) underline the critical need for appropriate definitions when models are constructed, subsequently recalling the traditional definitions utilized by leading geological institutions. Similarly, we consider essential to first raise the attention on some aspects of what a natural resource is, before we can define appropriately how it may be dissipated. We acknowledge that a huge number of publications have referred to this concept in several environmental, economic, social and law studies. Yet an exhaustive review of definitions of "resource(s)", as available in the existing literature, is out of the scope of this study.

Since the relevance of the concept of "resources" for the following analysis, we traced back on a non-exhaustive list of definitions to exemplify some key elements usually conveyed by different authors when referring to "resource(s)". A summary of such definitions is provided in Appendix A, as derived from Ardente et al., 2019). Although very heterogeneous (as presented in studies and publications with very different purposes), these definitions seem to converge to a common point: a "resource" is

considered as such when it has an intrinsic "value" or "utility" (i.e. by providing a certain function) for a certain subject (generally humans, in the common anthropogenic perspective). This value or function is not exclusively "economic" but it can range from the satisfaction of specific needs (e.g. the properties of a material for a production process) to the contribution to the overall human well-being (e.g. through the "cultural value" of resources). These considerations subsequently imply that input/output flows occurring in a life cycle inventory do not necessarily relate to "resources", in case these flows do not deliver any function or utility to the system while incidentally occurring in the process.

2.3 Resource dissipation in life-cycle based studies: status, from definition to implementation

This section firstly discusses the concept of resource dissipation as defined and implemented in the existing life-cycle based studies. These studies include MFA, SFA, LCA, and IO (Input-Output) Analysis. MFA, SFA and IO Analysis are closely interconnected: MFA is a general term including SFA, while IO Analysis can be used as a basis for Material Flow Analysis (so-called IO-MFA). In the following, the terms MFA and SFA are used when referring to the original developments in the field, while the term IO corresponds to any study based on IO Analysis, including what some authors refer to IO-MFA. This distinction enables to clearly identify IO Analysis as an approach which enables to account for both economic and physical exchanges in an economy and to allocate pressures to the environment (including resource extraction) to the final demand for goods and services.

The following discussion is based on a literature search performed through Scopus, online database of peer-reviewed scientific publications in English. Two keywords were combined in the query, and screened within title, abstract and keywords: firstly, one keyword related to the concept of dissipation (either "dissipation" or "dissipative"), and secondly one keyword referring to the method implemented (either using their entire name or only their acronyms; see Appendix A for the complete list of keywords used for the search). As a complement, several articles and reports that have not been identified through this search process, but that we considered of particular relevance, have been additionally selected and reviewed. On the contrary, a first screening of this full set of references has enabled to exclude some articles, when the concept of dissipation was treated marginally. Overall, the following analysis is based on 45 publications reviewed (see Appendix A for a complete list of publications reviewed and pieces of information drawn from the review process, on which the following discussion is based).

2.3.1 Scope of the studies

Most studies in the review aim at the analysis of flows and stocks of materials, applying standard Material Flow Analysis, sometimes targeting substances (SFA) or systems (MSA) instead of materials in a general sense. Overall, MFA (including SFA and MSA) is the method implemented in more than half of the cases (24 out of 45). The share of MFA studies dealing with the concept of resource dissipation even represented approximately 80 % of the articles published from 2002 to 2012 (Figure 2.1). From 2012 to 2018, a larger proportion of LCA, IO, and other approaches have tackled this issue as well, in particular highlighting the growing interest of the LCA-community on this topic. Moreover, 69 % of the publications apply an approach to a case study (in most cases namely applying MFA to a set of resources), while the remaining share aims at methodological developments. In particular, the majority of publications with LCA as the supporting method (9 out of 11) relate to methodological developments with respect to the accounting of resource use in the impact assessment.

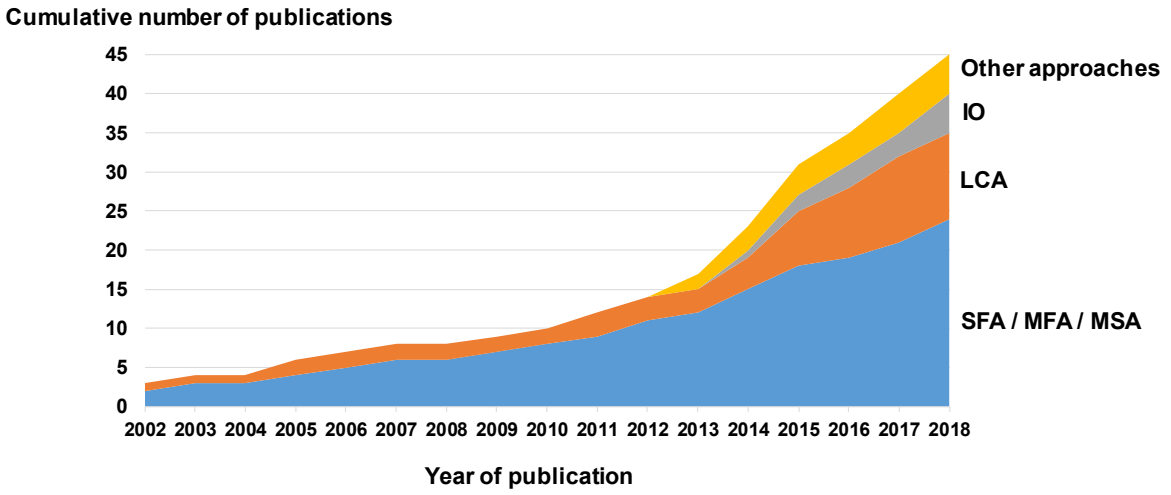

Figure 2.1 : The 45 life-cycle-based publications dealing with the concept of dissipation considered in the review, by type of method implemented and year of publication.

Overall, the reviewed studies dealing with the concept of dissipation mainly target abiotic resources. Most studies explicitly target a defined set of chemical elements, essentially metals. This is for example the case for most MFA studies, which aim at quantifying the flows and stocks of some given elements, in particular metals (e.g. zinc; Spatari et al., 2003; Tabayashi et al., 2008; Guo et al., 2010) but also other elements (e.g. fluorine, Villalba et al., 2007). In addition, a number of studies also apply or discuss the concept of dissipation with respect to:

- Other abiotic resources, such as fossil fuels (Krausmann et al., 2018; BIO by Deloitte, 2015) and non-metallic minerals (e.g. Stewart and Weidema, 2005), including aggregates (BIO by Deloitte, 2015);
- Biotic resources (e.g. wild or domesticated plants and animals in Stewart and Weidema, 2005; food for humans or feed for livestock, and biomass for thermal conversion in Krausmann et al., 2018).

Finally, in the context of discussions on the AoP natural resources for application to LCIA, several authors also discuss, or refer to, the concept of dissipation with considering a broader scope of resources in their study, including e.g. water, land, soil and water surface (Stewart and Weidema, 2005; Sonderegger et al., 2017; Sonnemann et al., 2015).

2.3.2 How “dissipation” is referred to? Commenting the lexical field used

In the reviewed publications, the concept of dissipation is analyzed and discussed with predominantly employing the term “dissipation” and its derivate terms: “dissipated” and “dissipative”. In many MFA case studies aiming at the assessment of metals stocks and flows, authors refer i) to the “dissipation of” the metal under study (e.g. dissipation of chromium in Johnson et al., 2006; indium dissipation in Stamp et al., 2014), ii) to the metal “dissipated” (e.g. copper dissipated in Spatari et al., 2005; germanium dissipated in Licht et al., 2015; alloying elements dissipated in Ohno et al., 2015), and iii) to the “dissipative” metal (dissipative zinc in Tabayashi, 2008; dissipative lead in Liang and Mao, 2014). When authors refer to dissipation in a more general sense, in particular tackling more than one resource either in a case study or in a methodological discussion, they often refer to “dissipative flows” (Lifset et al., 2012; Thiébaud, 2018; Müller et al., 2014), also termed “dissipation flows” (Johnson et

al., 2006), or “dissipative losses” (e.g. Rydh and Karlström, 2002; Spatari et al., 2002; Villalba et al., 2007; Guo et al., 2010; Ziemann et al., 2012; Zimmermann and Gößling-Reisemann, 2013; Kral et al., 2013; Licht et al., 2015; Zimmermann, 2017), sometimes using both interchangeably (Spatari et al., 2003; Ciacci et al., 2015; Kovanda, 2017). It is noteworthy that the term “loss” is also referred to in many publications without being directly associated to “dissipation” or “dissipative”. A clear connection is however often made between the two terms: for example, Stewart and Weidema (2005) define “resource dissipation” as a “loss of resource”, while Schneider et al. (2015) refer to “loss” of resources as a consequence of “dissipation”. Overall, two main cases can be distinguished:

a) for some authors, the concept of loss is intended to be broader than the concept of dissipation, that is “losses” account for, without being limited to, “dissipative flows” (e.g. BIO by Deloitte, 2015; Duygan and Meylan, 2015; Nakamura et al., 2014). For example, BIO by Deloitte (2015) define “losses” as the sum of three terms: i) outputs from the value chain (elements exiting the value chain “as impurities, non-functional by-product, dissipation…”), ii) in-use dissipation and iii) non-functional recycling;
b) on the contrary, other authors consider “dissipation” as a concept broader than “loss”. In this respect, Takeyama et al. (2016) evaluate the dissipation of chromium and nickel by summing the shares “lost” due to “physical and quality losses”. Moreover, Laner et al. (2017) refer to losses regarding different types of flows (e.g. “losses of phosphorous to landfills”) while the term “dissipation” refers more generally to a reduction in concentrations in the system, including due to “losses”.

Moreover, it is worth noting that whereas most authors refer to quantities of materials when using the term (dissipative) “loss”, others instead/also refer to losses in terms of quality (Paraskevas et al., 2015; Takeyama et al., 2016) or functionality (Stewart and Weidema, 2005; Sonderegger et al., 2017). Finally, several publications (e.g. Ziemann et al., 2012; Ciacci et al., 2015) include, or sometimes even focus on, “dissipative use”, also termed “in-use dissipation” or “dissipative applications”, which are described as specific uses or applications of the resource that directly lead to dissipation.

2.3.3 What is “resource dissipation”? One term, several definitions

Among the 45 publications considered in this review, 15 (33 % of the total) provide some definitions, most often explicit, of the concept of dissipation or of related terms. Table 2.1 lists the different definitions (in one case a definition was used in two publications). Instead, the remaining 30 publications do not explicitly define what they intend to capture as “dissipation”. The definition of dissipative flows is in these cases essentially implicit, with authors primarily classifying some flows as dissipative ‘per se’ (i.e. considering the concept as self-explaining and not necessitating further clarification).

Table 2.1 : "Resource dissipation" in the literature: a list of definitions

Authors	Definitions
Stewart and Weidema (2005)	Resource dissipation is defined as "the loss of resources from the technosphere in such a way that it is not possible to recycle them back into the technosphere."
Schneider et al. (2011)	"Dissipated stock is the amount of a resource that has been returned to nature in a form that makes recovery almost impossible"
Lifset et al. (2012)	The definition distinguishes between "dissipative releases, or releases from products that are not easily recovered or recycled; and dissipative uses, or those uses of a substance where the dissipative release is intentional"
Ziemann et al. (2012)	The definition focuses on dissipative use/applications. "A use or application of a metal is called dissipative when the metal is dispersed or scattered during the phase of use, making it exceptionally difficult and costly to recycle".
Zimmermann and Gößling-Reisemann (2013) and Zimmermann (2017)	"Dissipative losses for metals" are defined as "losses of material into the environment, other material flows, or permanent waste storage that result in concentrations in the receiving medium such that a recovery of these materials is technically or economically unfeasible."
Johansson et al. (2013)	"Dissipated metal resources [...] represent the share of employed metals that has been dispersed to the surrounding environment (land, sea, air or even space), often due to friction or turbulence such as copper corrosion from the roofs, metal leaching from landfills or zinc emissions from brake linings […]. Another type of dissipation is debris. While space debris primarily consists of abandoned space bodies […], marine debris tends to originate from human mishandling of discarded items such as waste escaping from landfills […]."
Kral et al. (2013)	"Dissipative material losses cover point and diffuse emissions with no option for recovery."
Müller et al. (2014)	The authors of this review article first refer to Ayres (1994): the category "metals that have been irrecoverably dissipated into soil, groundwater, or surface water" accounts for "material dissipation"; "materials are recycled or reused if economically and technologically feasible, otherwise they are eventually dissipated". Moreover, the authors mention that in the full set of studies they have reviewed, "dissipative flows" are generally described as in Ayres (1994) or referred to "as emissions, loss flows, stock leakage or specific flows to landfills or the environment".
Stamp et al. (2014)	"Dissipation is defined as a dilution to the extent that recovery is impossible with known technologies."
BIO by Deloitte (2015)	The authors state that losses are composed of: i) Output from the value chain: "annual quantity of the element exiting the value chain (as impurities, non functional by-product, dissipation, ...)"; ii) In use dissipation: "refers for example to: a loss of zinc due to corrosion of zinc coating on steel, a loss of copper due to spread of copper sulphate as a fungicide"; iii) Non functional recycling: "refers to recycling in which the element in a discarded product is collected and incorporated in an associated large magnitude material stream. This represents the loss of its function as it is generally impossible to recover it from the large magnitude stream"
Ciacci et al. (2015)	"dissipative losses are the flows of materials from the anthroposphere (i.e., human systems) to the biosphere (i.e., environment) in a manner that makes their future recovery extremely difficult, if not impossible"
Sonnemann et al. (2015)	A resource is "dissipated" when it "is made unusable as such for future users"

Kovanda et al. (2017)	The dissipative flow account consists of: - "Dissipative use of products" which comprises “materials released into the environment on purpose in order to increase the production capacity of agricultural land, for instance. [...] Dissipative use of products for the Czech Republic comprised consumption of mineral fertilizers [...], manure [...], pesticides [...], seeds used for sowing [...], composts, use of sewage sludge as fertilizer [...] and consumption of thawing materials" - and "Dissipative losses”, which “include corrosion and abrasion of products and infrastructures, leakages, emissions from the use of solvents, etc."
Sonderegger et al. (2017)	Commenting articles in their discussion of the literature, the authors state that "If the natural resource is dissipated into concentrations that are below a threshold that allows for recovery, it is lost and the stock decreases." Later in their discussion, they mention that: "Natural resources and (raw) materials are lost if the required qualities for their functionality are lost (e.g., through dissipation).”

Among the 14 definitions, 9 use the term “recover” (or its derivate terms, such as “recovery”), and 5 the term “recycle” (instead of, or as a complement to, the term “recovery”). Dissipation of a resource is therefore primarily related to the difficulty, or even to the impossibility, to recover it. On the one hand part of the authors consider that, even if the resource is recoverable, it may be set to be dissipated in case of an extreme / exceptional difficulty to recover it. Accordingly dissipation is said to occur when the recovery or recycling is not easy (Lifset et al., 2012), “exceptionally difficult and costly” (Ziemann et al., 2012), “extremely difficult, if not impossible” (Ciacci et al., 2015) or “almost impossible” (Schneider et al., 2011). On the other hand, other authors clearly mention the impossibility for the resource recovery: the recovery or recycling is said to be “not possible” (Stewart and Weidema, 2005), “impossible” (Stamp et al., 2014) or “unfeasible” (Zimmermann and Gößling-Reisemann, 2013; Zimmermann, 2017), while some other authors additionally mention the terms “irrecoverably” (Müller et al., 2014), “no option for recovery” (Kral et al., 2013) and “below a threshold that allows for recovery” (Sonderegger et al., 2017) in their definition of dissipation. Finally, in some cases (e.g. BIO by Deloitte, 2015; Kovanda, 2017) authors provide partial definitions in which different types of dissipation are listed and supported by an extensive list of examples.

2.3.4 Which temporal perspective to assess dissipation? On the static/dynamic nature of dissipation

Several of the publications considered in the review implement a dynamic modelling of flows and stocks, for example considering assumptions on the implementation of improvements in technology (Nakamura et al., 2014). Moreover, regarding the assessment of these flows as “dissipative” or on the contrary “non-dissipative”, several authors refer to temporal aspects directly within the definition they provide for the concept of “dissipation” (Table 2.1), or as complements to this definition. In particular, Ciacci et al. (2015) define dissipative flows as those for which “future recovery [is] extremely difficult, if not impossible”. Similarly, Stewart and Weidema (2005) refer to “resources made unavailable […] for any foreseeable future use by society”, while Sonnemann et al. (2015) consider a resource as dissipated when it “is made unusable as such for future users”. Moreover, Zimmermann and Gößling-Reisemann (2013) add a "dynamic element” in their definition of dissipative losses ("losses that must be considered dissipative today might be less dissipative in the future"), which they link to the time-dependent technical and economic feasibilities of recovering a material, in line with some other authors (e.g. Lifset et al., 2012). They additionally mention the residence time as a qualitative

parameter to classify dissipation types, with “long residence times […] increasing the severity of dissipation" (Zimmermann and Gößling-Reisemann, 2013). Yet, it is noteworthy that the majority of authors (69 % of publications) on the contrary do not refer to any temporal aspect in their approach to dissipation. Moreover, even in the cases where these aspects are mentioned, this is primarily done in very general terms. In particular, none of the publications reviewed explicitly mentions a given (valued) temporal perspective, for application to the quantification of dissipative flows.

2.3.5 Where are resources dissipated? Distinguishing three compartments of dissipation

Among the publications considered in this exercise, 73 % account more or less explicitly for dissipative flows to (or within) one of the three following compartments:

- environment, which relates to what is usually called “emissions to the environment” in MFA and LCA studies. For example, emissions of copper associated with its mining and production and with its use in specific applications (e.g. pesticides, fertilizers, fireworks, brake pads, etc.) are considered to be dissipative flows to the environment (Lifset et al., 2012). Environment is the compartment mostly addressed in life-cycle-based studies dealing with the concept of dissipation (considered in 62 % of studies, including 31 % as a single compartment; Figure 2.2);
- final waste disposal facilities (in technosphere), considered in 36 % of studies. This in particular corresponds to landfills and tailings management facilities (e.g. critical metals with a share dissipated to slags disposed of in landfills; Thiébaud et al., 2018);
- products in use (in technosphere), considered in 33 % of studies. This category corresponds to two main types of flows. Firstly, for some authors (e.g. BIO by Deloitte, 2015; Paraskevas et al., 2015; Takeyama et al., 2016; Laner et al., 2017), this category aims at accounting for “dissipation” or “losses” due to non-functional recycling, that is the “collection of old metal scrap flowing into a large magnitude material stream, as a “tramp” or impurity elements”, representing the “loss of its function” according to the United Nations Environment Programme definition (UNEP, 2011). For example Takeyama et al. (2016) state that nickel and chromium used in special (alloy) steel are expected to be dissipated when recycled to ordinary steel. Yet, it is noteworthy that some other authors instead exclude non-functional recycling as a form of dissipation (e.g. Ciacci et al., 2015). Secondly, the category “products in use” aims at accounting for dissipation (dispersion/dissolution) in products (e.g. indium used in solders and alloys; Licht et al., 2015), as a driver of subsequent dissipation later in the life cycle (e.g. “at the end of life” as in Licht et al., 2015; and/or through emissions to the environment during the product use; see also Zimmermann and Gößling-Reisemann, 2013 and Zimmermann and Gößling-Reisemann, 2014; Duygan and Meylan, 2015; Ohno et al., 2015). Such an accounting of dissipation in products in use however overlaps with the dissipation in final waste disposal facilities and emissions to the environment as considered by some other authors (and as listed above). Finally, as a specific additional type of dissipation in products in use, Zimmermann and Gößling-Reisemann (2013) and Zimmermann (2017) consider the impossibility to access the material embodied in a product in use, introducing the concept of short and long residence time in their discussion of resource dissipation.

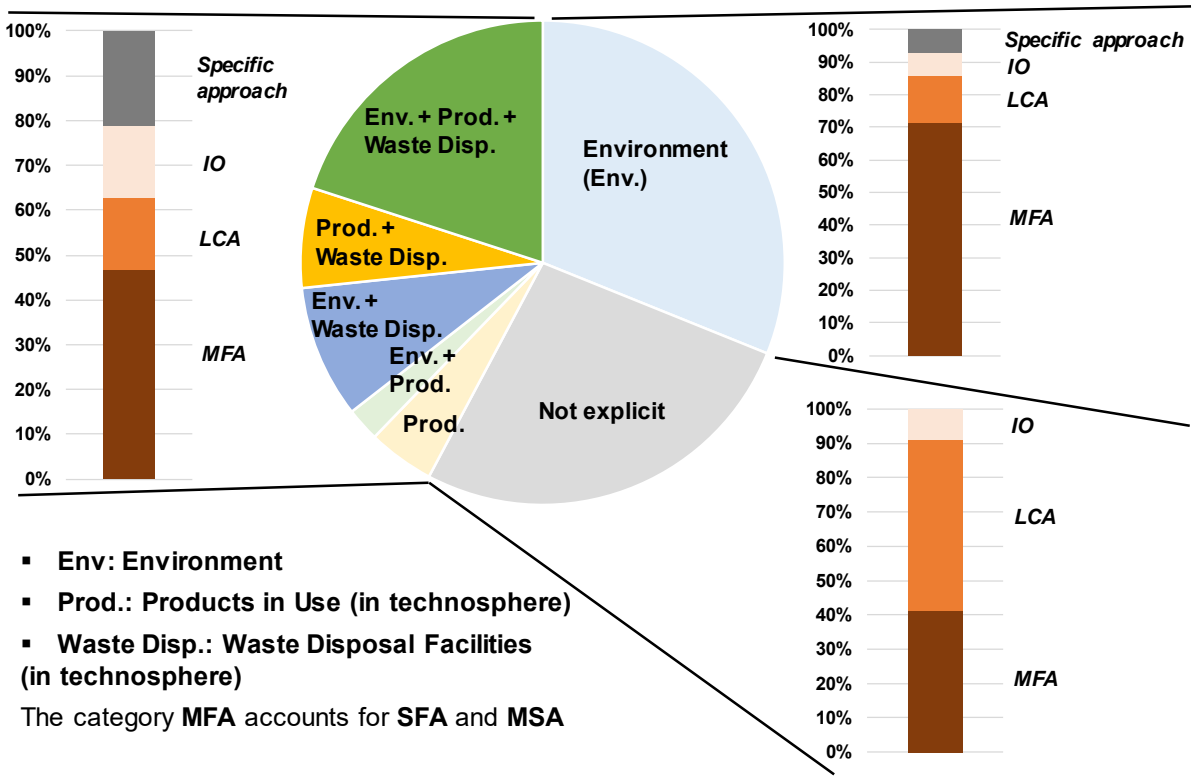

Figure 2.2 : Where are resources dissipated? Shares of compartments of occurrence in the 45 publications reviewed, as a function of the method implemented.

Among the publications that consider emissions to the environment as the only dissipative flows, two thirds relate to MFA (including SFA and MSA) studies (Figure 2.2). Linking this result with the trend of Figure 2.1, one observes that the life cycle community has generally considered in the past that dissipative flows were restricted to emissions to the environment. In their original developments, in the early 2000s, SFA studies also sometimes reported the flows of materials or substances to landfills and tailings, nevertheless without necessarily associating them with the concept of "dissipation" (e.g. Rechberger and Graedel, 2002; Rydh and Karlström, 2002; Spatari et al., 2003, 2005).

On the contrary, the share of each type of method is relatively more balanced regarding the studies accounting for dissipation in products in use and in waste disposal facilities (Figure 2.2). The recent increasing interest of IO and LCA communities on the concept of "dissipation", as observed in Figure 2.1, has tended to reduce the share of "environment" as the only compartment considered for dissipative flows. Also, a number of recent SFA studies have considered compartments beyond environment when referring to dissipation (e.g. Licht et al., 2015; Ciacci et al., 2016; Thiébaud et al., 2018) contrarily to most of the SFA studies performed in the early 2000s. Finally, LCA is the method for which the type of compartments is the least explicitly addressed (Figure 2.2): a number of LCA publications mention the concept of dissipation when discussing the impacts of the studied system due to resource use, yet without referring where these dissipative flows occur.

2.3.6 Which approaches are implemented to assess "resource dissipation" in a system?

Most authors define a set of flows that they consider "dissipative", and then quantify them based on different types of data (statistics, process data, assumptions, etc.). On the one hand, some authors provide some or even several examples of dissipative flows, considered as self-explanatory and related

to a common understanding of the dissipation concept, e.g. relating to the use of minerals in fertilizers (Zimmermann and Gößling-Reisemann, 2013; Ciacci et al., 2016; Ciacci et al., 2015; Kovanda, 2017; Laner et al., 2017; Krausmann et al., 2018), to the dissipation of certain metals when used in alloys (Zimmermann and Gößling-Reisemann, 2013; Licht et al., 2015; Ohno et al., 2015; Paraskevas et al., 2015; Takeyama et al., 2016; Nakamura and Kondo, 2018), or due to corrosion or abrasion (Schneider et al., 2011; Johansson et al., 2013; Kral et al., 2013; BIO by Deloitte, 2015; Ciacci et al., 2015; Kovanda, 2017). On the other hand, some authors use a generalized approach to classify dissipative flows, based on simplified assumptions. For example it is assumed that: all the flows to the environment (Arvidsson et al., 2011; Spatari et al., 2005; Johnson et al., 2006), or flows to tailings and slags (Liang and Mao, 2014) or flows to landfills (Zimmermann and Gößling-Reisemann, 2014) are dissipative. Finally, as a generalized approach at a more aggregated level, Vadenbo et al. (2014) suggest calculating the dissipative use of resources in LCA as "the difference between the amounts of resources extracted and recycled".

However, in none of these studies the rationale for flagging flows as "dissipative" is quantitatively discussed, in particular entailing the risk of being non-exhaustive. Considering the definitions provided in the literature (Table 2.1), we may assume that this classification is based on the authors' own evaluation of the difficulty, or even the impossibility, to recover the resource considering the flows at stake. Only a few authors mention parameters and thresholds to clearly distinguish dissipative flows from non-dissipative ones. Stewart and Weidema (2005) in particular mention concentration and mineralogy regarding metallic minerals, and particle size regarding non-metallic minerals, as parameters to assess dissipation in light of "ultimate quality limits". Zimmermann and Gößling-Reisemann (2013) and Zimmermann (2017) mention concentration as a determining parameter in their definition of dissipative flows (Table 2.1), while Vadenbo et al. (2014) refer to recovery costs and resource concentrations as potential criteria to draw the boundary between borrowing and dissipative uses. Finally, Rechberger and Graedel (2002), Laner et al. (2017) and Thiébaud et al. (2018) are the only authors implementing a quantitative approach to case studies, namely using Relative Statistical Entropy (RSE) to express the ability of a process or of a whole system to dissipate a resource, as also mentioned in UNEP (2013). Yet this approach has not been used to distinguish dissipative flows from non-dissipative flows (that would be both expressed in mass terms), but rather to quantify dissipation along a system (using RSE as the metric).

2.4 Resource dissipation: a definition, and the key challenges it implies for implementation in LCA

This section firstly provides a definition for resource dissipation, building from the literature review and specifically focusing on abiotic resources (that is, fossil and mineral resources). Then, the concept of dissipation is discussed with respect to its potential implementation in LCA, distinguishing three determining features as considered in the above literature review: the temporal perspective, the different compartments towards which resources are considered to be dissipated, and the approach implemented to assess dissipative flows in the system under study.

2.4.1 Terminology and definition

The literature review highlighted the absence of a common definition of resource dissipation across all reviewed studies, with relatively large deviations from one study to the other. In this context, we propose a comprehensive definition for dissipation of abiotic resources, building on several definitions in the literature, to reflect relevant features as discussed in previous sections:

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.

In particular, we have chosen to use the terms "dissipative flows" instead of generally referring to "dissipation" or "losses" (and their derivate terms, such as "dissipative losses"), primarily because they appear more connected to the topic addressed (resource dissipation) than any reference to "losses". Moreover, the focus on flows is in line with the core practice of LCA of investigating exchanges of products and elementary flows between unit processes in the technosphere and the environment. Yet, we acknowledge that there may be some cases where the use of the term "loss" may be considered more understandable and therefore still appropriate, e.g. when communicating LCA results to a non-technical target audience.

When putting this definition in perspective with the above discussions on the concepts of "resources" and "dissipation" as in the literature, it is noteworthy that it refers to:

- the function a resource may have. For example the mass of any metal along the life cycle of a system remains constant (atoms of metals never "disappear"), and as such still hold a potential value for humans. Yet metals (considered here as "resources") can be dissipated, whenever the functions these metals can have for humans in the technosphere are rendered inaccessible to future users along the life cycle of a system;
- the temporal dimension (mentioning "not accessible to future users", "which may change over time"), therefore making the timeframe an element to be considered when quantifying resource dissipation;
- "flows to sinks or stocks", therefore implicitly encompassing flows to the three compartments most commonly distinguished in the literature: environment, products in use and waste disposal facilities;
- "different constraints" which include, but are not limited to: change in physico-chemical properties; low concentrations and large spatial spreading; complex chemical and mineralogical compositions (e.g. presence of contaminants); heterogeneity and limited knowledge on sinks composition and localization which hinder the chance of their recovery;
- "technological and economic factors" as potential determinants to distinguish "dissipative flows" from "non-dissipative flows". Yet this definition is also open to a purely physical understanding of the concept of dissipation, which could e.g. consist in directly identifying dissipation to entropy/exergy changes along the system under study, therefore beyond considering such entropy/exergy changes as markers of dissipation.

2.4.2 Which temporal perspective to assess resource dissipation in LCA?

The reference to "future users" and to time-dependent (technological and economic) factors in this definition implies that, when assessing resource dissipation over the life cycle of products and systems, the timeframe considered should be i) determined when defining the scope of the analysis (based on the answer to the question: which future users are considered in this assessment?) and ii) explicitly reported. This timeframe potentially has key implications on the technological and economic capacity to make use of the function of a resource, and subsequently on the assessment of dissipative and non-dissipative flows in a system.

Despite a precise specification of the timeframe to be considered is out of the scope of this chapter, it is noteworthy that:

- A very short timeframe would consider recycling performances at the time of the assessment and would assume that all the resources ending to final sinks (e.g. landfills, tailings), and not currently recovered, are dissipated. Such timeframe would be representative of the current situation (by definition), and would potentially convey a relatively high precision in the modelling of resource dissipation thanks to good data quality. However, it would disregard the fact that part of these sinks could be potentially exploited in the future (e.g. landfill mining), with a certain efficiency (therefore potentially lowering the accuracy of the modelling);
- A very long (or even infinite) timeframe could imply the assumption that, regarding any flow of resource currently unrecovered, there is a chance that future technological improvements will make it potentially functional again for humans. However, this chance is always mainly theoretical and very difficult to assess "a priori", especially concerning the efficiency of processes and the characteristics of the recovered materials.

In the context of LCA, the timeframe considered to assess resource dissipation needs to be consistent with the goal and scope of the study, with potential influence on both the inventory and the impact assessment steps. In the new approaches to account for resource dissipation in LCA, several timeframes could be set for further choice and use by LCA practitioners, as is the case for some other impact categories.

2.4.3 Which compartments to assess resource dissipation in LCA?

The definition of resource dissipation broadly encompasses "flows to sinks or stocks that are not accessible to future users". Accordingly, it includes emissions to the environment, flows to products then used in the technosphere and flows to waste disposal facilities, under two conditions: i) they are flows of resources and ii) they are made inaccessible to future users. For certain flows it could be not straightforward to define if this is an emission to the environment or within the technosphere. For example, copper used as pesticides and spread in agriculture could be considered as dissipated in the environment (as air emissions) or in the technosphere (as contaminant in a cultivated field). Actually, whatever the compartment of occurrence, the dissipative flows could be assessed considering a common temporal perspective (as discussed in the previous section 2.4.2) and a common set of parameters (as discussed in the next section 2.4.4). Yet specifying the compartment can be relevant to better understand where dissipation occurs in a system ("what ends where"), and also to differentiate among "dissipative" or "non-dissipative" flows based on general, shared, rules (e.g. setting by default that all emissions to the environment could be considered dissipative).

The LCA framework and the current LCI databases overall distinguish emissions to the environment and products end-of-life (including recycling and waste disposal), in particular including some data that could be used to support the assessment of resource dissipation. Firstly, emissions to the environment are usually traced and documented in LCIs. These data, in mass units, could be considered as a basis to identify and quantify resources dissipated to the environment. However, not all emissions to the environment are necessarily dissipative flows of resources. Only the emissions of resources (which have held a function and/or an instrumental value along the system life cycle, by definition) can be potentially dissipative. For example, part of the heavy metals embodied in copper mineral ores which are displaced from the underground to other compartments through the process of copper concentration (e.g. to tailings or to air, as dust emissions from the process) are not exploited and do not act as "resources" along the system. They are potentially relevant regarding toxicity aspects (Beylot

and Villeneuve, 2017), but could be disregarded with respect to their contribution to resource dissipation.

Moreover, LCA accounts for the end-of-life of the product or system under study, and of all the products and systems interlinked with it. This firstly implies accounting for the generation of waste and their recycling at the end-of-life. If possible, this analysis should also evaluate the degradation ("downcycling") of the recycled materials' functions (suggested, for example, as best practice by the ILCD Handbook; EC-JRC, 2010). The estimation of the "degradation" of resources (i.e. the changes of their functionality due to e.g. non-functional recycling, in quantitative and qualitative terms), have been used so far in LCA and Ecodesign studies to quantify potential environmental credits to recycling (Allacker et al., 2014; Ardente and Mathieux, 2014). These could be additionally used as a basis to estimate the mass of resources dissipated in the products in use within the technosphere. Further developments would however be necessary to systematically identify the cases for which the degradation of a resource is such that it is "dissipated" (e.g. setting appropriate metrics and thresholds). Moreover, LCA accounts for flows to waste disposal facilities (including in particular municipal solid waste, bottom ashes or slags landfilling, and waste from mineral processing disposal in tailings disposal facilities). Currently the LCI modelling primarily aims at providing the corresponding emissions to the environment (e.g. under the form of leachates). As best practice these emissions are derived considering both the mass and composition of the waste disposed of (see e.g. Doka, 2009). Yet, the information on the elemental composition of waste, used to calculate these emissions to the environment, is usually considered as background data at best only reported in the documentation supporting the database. Such a piece of information could be considered a basis to be further used, and completed, in order to account for resource dissipation in landfills and tailings disposal facilities in future LCA.

Finally, it is noteworthy that in the LCA context, the dissipative flows of resources may need to be allocated between co-products of a multi-functional process, like any other pressures to the environment (e.g. emissions to the environment). The used allocation key may accordingly influence the assessment of resource dissipation along the life cycle of the product or system under study.

2.4.4 Which approaches are used to assess "resource dissipation" in a system in LCA?

2.4.4.1 Constraints leading to dissipation

The above proposed definition reports "different constraints" as drivers for resource dissipation, with mentioning "technological and economic factors" regarding the "distinction between dissipative and non-dissipative flows of resources". The chemical elements composing a resource are not "consumed" nor transformed: whatever the process, the mass of any chemical element composing a resource remains constant. On the contrary, mineral resources can be dissipated when they are rendered inaccessible to future users (by definition of "resource dissipation"). The constraints evoked (e.g. low concentrations and large spatial spreading; complex chemical and mineralogical compositions; etc.) imply technological limitations (absence of a suitable technology to process the flows and to make them further usable) and/or economic limitations (technology not economically viable) within the timeframe of the assessment, even when the form and mass of the original resource remains constant in the system under study (e.g. rare earths elements in permanent magnets of waste Hard Disk Drives; Thiébaud et al., 2018). Moreover, technological and/or economic limitations may be dependent on the localization of the potentially dissipative flows (e.g. landfill mining being/becoming technologically feasible and economically viable in some geographical contexts only). Accordingly the geographical

representativeness of the model to account for resource dissipation in LCA should be consistent with that generally used to model the LCI system, which depends on the goal of the study and its intended applications (as in the case of the timeframe).

2.4.4.2 Parameters and thresholds to account for these constraints in LCA

In the reviewed publications, most authors define a set of flows that they consider "dissipative" per se, whereas some others have mentioned/applied several parameters to assess dissipative flows (concentrations, mineralogy, particle size, recovery costs and statistical entropy parameters) as more advanced approaches. However, existing LCI datasets are currently not featured to neither of the two accounting approaches. Firstly, exchanges of products within the technosphere include e.g. flows to landfills or to tailings while elementary flows from the technosphere to the environment include e.g. emissions to air, water and soil. Nevertheless, none of these exchanges are currently referred to as "dissipative" in LCI databases. Moreover, the parameters mentioned and even sometimes used in the literature to assess dissipative flows are also absent from LCI databases. The latter could therefore be completed and adapted with such types of information and parameters, yet by means of probably significant efforts. In the meantime further research will be necessary to assess their relevance, including the potential setting of thresholds beyond which one may consider a flow as dissipative.

2.5 Conclusions and potential way forward

The concept of resource dissipation has gained increasing interest in the last two decades in life-cycle based studies. This chapter shows that while most definitions in published studies intend to capture the difficulty/impossibility to recover a resource, there are different understandings of when a resource is actually difficult or impossible to be recovered and should accordingly be considered "dissipated". Firstly several authors refer to temporal aspects in their definitions, or as complements to their definitions. However in most cases no temporal aspect is referred to; and when referred to, no given (valued) temporal perspective is explicitly mentioned. Moreover most publications account more or less explicitly for dissipative flows to (or within) at least one of the three following compartments: environment (which relates to what is usually called "emissions to the environment" in MFA and LCA studies), final waste disposal facilities (in technosphere), and products in use (in technosphere). Finally, in order to quantify dissipative flows in the system under study, most authors define a set of flows that they consider "dissipative", and then calculate the corresponding masses based on different types of data (statistics, process data, assumptions, etc.).

In the absence of a commonly agreed definition of the concept of resource dissipation and of a consistent implementation, its application in LCA is still at a standstill today. In this chapter, we propose a comprehensive definition for this concept, building from the literature review, and we then discuss this definition with respect to its potential implementation in LCA considering today's existing datasets and best practices. The LCA framework overall appears well suited to account for resource dissipation. In particular, current LCI datasets cover the flows to the three main compartments of dissipation as distinguished in the literature. However, major challenges are still faced before resource dissipation can actually be routinely, and precisely, assessed. No flows are currently referred to as "dissipative" in LCI datasets, but the latter and their supporting information documents are sources of information that could be further used and completed to potentially account for dissipative resource flows. Moreover the addition of new parameters to evaluate dissipation (e.g. concentrations, mineralogy or entropy, as sometimes mentioned in the literature of life-cycle-based studies) would probably require significant efforts in the context of LCI databases.

These challenges may be overcome, for example, through several steps in a sort of “research agenda” from short-term to long-term. In the short-term, existing LCI databases may be used considering simplified approaches. As a first simplification, one may consider calculating the difference between the amounts of resources extracted and recycled at the level of the whole life cycle, as a proxy for the total amount of resources dissipated. Yet, by definition, this is a simplification that does not allow to assess the contributions of the different life cycle stages or processes to the total dissipation along the whole life cycle. Another simplification could be to flag some flows (to the environment, products in use or waste disposal facilities) as dissipative per se, as done so far in some MFA studies (e.g. considering that emissions of metals to the environment or flows of metals to landfills are entirely dissipative and accordingly flagged as such in the LCI). These simplifications could be defined and shared to be systematically applied in LCA. Such an approximation may be particularly consistent for some flows, such as in the case of resources dissipated to the environment, which are dispersed in very low concentrations and represent small, poor-value, deposits. In parallel, new possible approaches to quantify dissipative flows will need to be tested, with application to case studies. This implies, in particular, testing and analyzing several different approaches with respect to the temporal perspective (short, mid or long-term perspectives), the parameters and the thresholds set to quantify resource dissipation.

In the mid-term, these case studies may enable to evaluate the soundness of such approaches, including their robustness and the potentiality for their generalization (for example regarding the feasibility of new data collection to complement existing LCI databases). Additionally, these case studies may foster discussions towards reaching a common understanding on the concept of resource dissipation and its related features, which is essential prior to any large-scale implementation in LCA. Methods to characterize the impact of resource dissipation will need to be developed and tested as well. So far, existing life-cycle-based studies have focused on the assessment of quantities of resources dissipated, primarily in mass units.

Finally, in the long-term, large-scale changes of LCI databases may be required (e.g. updating the existing datasets with new data related to dissipation) considering one or several of the approaches identified as relevant in the “mid-term step”. These changes in LCI datasets will eventually offer the possibility for LCA practitioners to use proper background data in their modelling, and accordingly to systematically account for abiotic resource dissipation in LCA.

3 Chapter 3 – The JRC-LCI method: dissipation of mineral resources in Life Cycle Inventories

This Chapter is essentially drawn from:

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Contribution of the co-authors:

- Antoine Beylot: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.
- Fulvio Ardente: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.
- Serenella Sala: Conceptualization, Writing - review & editing.
- Luca Zampori: Conceptualization, Methodology, Investigation, Writing – original draft, Writing - review & editing, Visualization.

3.1 Introduction

Building on and expanding the feasibility study of Zampori and Sala (2017), this chapter proposes a new approach to account for dissipative resource flows in the Life Cycle Inventory (LCI) of a product. Firstly, the definition of mineral resources is discussed considering both current main LCA practice and the specific context of resource dissipation. Then, the approach is detailed and its practical operationalization in LCI databases is discussed. Finally this approach is applied to the case of the cradle-to-gate production of primary copper, and further discussed considering three main angles: i) how it would change the interpretation of results regarding mineral resources in LCA, ii) how far some key methodological aspects of this approach (e.g. the temporal perspective) can affect the inventory results, and finally iii) the issue of new data requirements, in terms of availability and adequacy.

3.2 Mineral resources, dissipation: defining the concepts in the context of LCA

3.2.1 Mineral resources: current concept in LCA

The TF mineral resources of the UNEP Life Cycle Initiative defines "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" (Berger et al., 2020). This definition leaves room for further interpretation in the LCA of a product: the same product system (e.g. copper sheets and aluminium sheets) can be represented by use of different inputs of mineral resource elementary flows from the ecosphere (e.g. respectively copper or chalcopyrite and aluminium or bauxite) at the LCI stage.

3.2.2 Abiotic resource dissipation: concept in life-cycle-based studies

Chapter 2 (Beylot et al., 2020b) describes the status of resource dissipation in the literature of life-cycle-based studies (that is, studies that trace the flows of resources from their extraction to their end-of-life), in particular identifying three main features:

i) several authors refer to temporal aspects in their definitions, or as complements to their definitions. However in most cases no temporal aspect is referred to; and when referred to, no specific temporal perspective is provided;

ii) most publications account more or less explicitly for dissipative flows to (or within) at least one of the three following compartments: environment, which relates to what is usually called "emissions to the environment" in MFA and LCA studies; final waste disposal facilities (in technosphere); and products-in-use (in technosphere), mainly associated with "non-functional recycling" (i.e. the incorporation of a material, as a "tramp" or impurity element, in a larger material stream; Beylot et al., 2020b);

iii) in order to quantify dissipative flows in the system under study, most authors define a set of flows that they consider "dissipative", and then calculate the corresponding masses based on different types of data (statistics, process data, assumptions, etc.).

Moreover, building on this literature review, Beylot et al. (2020b) provide the following definition (see Chapter 2, section 2.4.1):

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.

3.2.3 Mineral resources: concept in LCA, adapted to account for dissipation

The definition of the TF mineral resources of the UNEP Life Cycle Initiative opens the door to the consideration of mineral resource elementary flows in several diverse ways in LCIs (e.g. in the form of a mineral in the ore, of the elements contained in this mineral or both mineral and contained elements; Berger et al., 2020). Therefore, it is essential to set what is intended as "mineral resource flows" in this study. Firstly, the focus is here set on "dissipative", "natural" resource flows. This is in line with the issue of concern in this study (resource dissipation), and consistent with the Area of Protection (AoP) "Natural Resources" in LCA. This implies that man-made materials (e.g. steel) are not considered as resources in the following, but rather as made of resources (e.g. steel made of iron and several other elements, such as carbon, chromium and nickel). It is noteworthy that despite "natural", "resources" can be primary (when extracted from the ecosphere) or secondary (when produced from the technosphere; Berger et al., 2020).

Following these considerations, a set of rules is suggested to enable identifying and tracing mineral resources in the life cycle of products, and subsequently to account for their dissipation. It is noteworthy that these rules are necessary to apply the approach described in the following sections to account for resource dissipation in LCA. However, other rules could have been set, compliant with the definition of the TF mineral resources and also enabling to account for resource dissipation in LCA.

- Regarding primary mineral resources: *i)* "if the mineral or aggregate has a value as such (e.g. gypsum or sand), the mineral is considered the relevant elementary flow" (Berger et al., 2020), that is to say it is the resource; and instead *ii)* if the value of a mineral ore is to host elements only, there are different views on what should be considered the resource(s) (as reflected by the definition of the TF mineral resources): either the mineral (e.g. chalcopyrite) and/or the totality (or some) of the elements contained therein (e.g. copper). In this study, the target elements in the ore are considered to be the resources (as in the ecoinvent 3 database; Weidema et al., 2013);
- Regarding mineral resources in use in the technosphere, and potentially valuable as secondary resources: as long as the chemical elements, minerals and aggregates hold their original, or a significant, value in the product system under study, they are resources. This enables to account for secondary resources in the product system: not only primary resources can be dissipated, but more generally any chemical element, mineral or aggregate which provides its original or a significant function in a product-in-use;
- Finally, as a basis, the list of mineral resource flows derives from the EF reference package (version 3.0; EC, 2019), considering all minerals classified as "resources from ground".

3.3 Method

3.3.1 Rationale: dissipative flows at the unit process level

The approach consists in reporting the dissipative flows, in mass units, at the unit process level (that is, at the level of the "smallest element considered in the life cycle inventory analysis for which input and output data are quantified"; EC-JRC, 2010). A list of dissipative flows of mineral resources is predefined, in the form: "dissipative flow of mineral resource x to compartment y" (with e.g. x = copper and y = environment). Dissipative flows can be both elementary flows (exchanges from the technosphere to the ecosphere) and exchanges within the technosphere (from the technosphere to the technosphere). Assuming that R mineral resources are distinguished in the LCI framework, and C

compartments (e.g. environment, landfills, tailings disposal facilities, etc.), the total number of dissipative flows distinguished equals R x C. This approach is in line with most of the studies which have dealt so far with resource dissipation in MFA and SFA, in which a set of dissipative flows is usually predefined before the corresponding masses are calculated based on different types of data (Chapter 2; Beylot et al., 2020b). Moreover, this approach is also consistent with the accounting of other elementary flows in LCI datasets, with a predefined list of flows for which a physical (usually, mass) value should be reported at the unit process level.

3.3.2 Temporal perspective considered in this study

In this article, the temporal perspective considered to assess resource dissipation is set to a rather short-term, that is 25 years. Said in other words, a resource is considered to be dissipated when it is rendered inaccessible to any future user within one generation. It is recalled that, as common practice in LCA (e.g. in the PEF/OEF; Zampori and Pant, 2019), the exchanges with the ecosphere/technosphere along the life cycle of a product are integrated over the lifetime of the product under study, and considered to occur at the time the LCA study is conducted. This implies that the 25-year perspective applies to the whole dissipative resource flows over the life cycle of the product under study, considered to occur when the study is carried out.

It is noteworthy that the shorter the temporal perspective, the more reliable the assessment of the resource accessibility to future users. The consideration of longer-term perspectives could fit as well with the general rationale of the approach presented in the previous section (reporting of dissipative resources at the unit process level, considering a pre-defined set of dissipative flows). However, despite potentially adapted to the goal and scope of some LCA studies, long timeframes imply uncertainty on the potential accessibility of resources to future users (related to uncertainty on future potentially economically viable technologies), and are only considered as a sensitivity analysis in this study.

3.3.3 Dissipative flows in this temporal perspective

In a short-term perspective, any flow of resources *i)* to the environment (air, water and soil), *ii)* to final waste disposal facilities and *iii)* to products-in-use in the technosphere in which the resource provides a low function, can be reasonably assumed to be “not accessible to future users” (i.e. dissipative). Accordingly these dissipative flows need to be reported in mass units at the unit process level when constructing LCI datasets (Figure 3.1). This approach is in line with the literature of life-cycle based studies which, in the recent years, have increasingly accounted not only for dissipative flows to the environment but also for dissipative flows to final waste disposal facilities and products-in-use in the technosphere (Chapter 2; Beylot et al., 2020b).

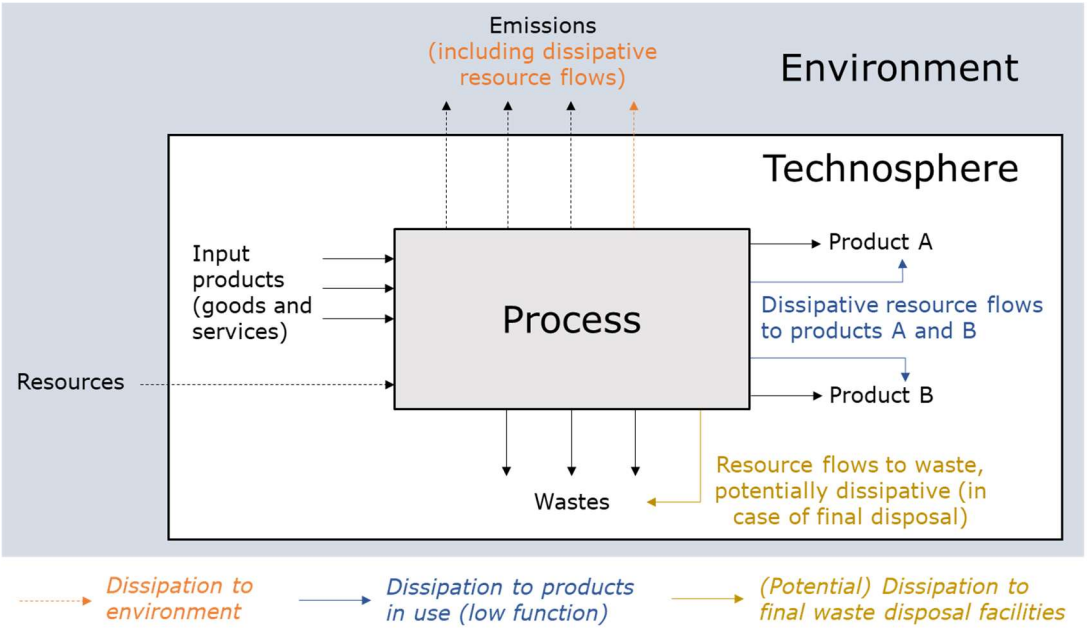


Figure 3.1 : Flows at the unit process level: general scheme (from EC-JRC; 2010) modified to account for dissipative flows to three main compartments

3.3.3.1 Dissipation in products-in-use

It is noteworthy that in the literature, dissipation in products-in-use (in technosphere) mainly corresponds to "non-functional recycling" (Chapter 2; Beylot et al., 2020b). In this article, the concept of dissipation in products-in-use is instead extended to "low-functional recovery" in order to include not only "non-functional recycling" but also other cases of recovery that depart from recycling, for which the recovered material provides such a low function compared to its potential functions (and accordingly, value) that it is not a resource. It is considered that this reduction in functionality is associated with the absence of any technologically feasible and/or economically viable process to recover the original, or any significant, function(s) and associated value of the resource in the temporal perspective considered (that is, 25 years), overall making the resource dissipated.

In order to define whether a resource flow to a product-in-use is dissipative or not, LCA practitioners should first assess the potential function of this resource. For example, when slags from a copper smelter are used in construction, they fulfil the function of (and substitute for) natural aggregates. In that case, copper embodied in slags can be considered as recovered with low functionality, with the impossibility to recover the original, or any significant, value of the resource in the temporal perspective considered (absence of any economically viable technology); i.e. it is a dissipative flow (Table 3.1). On the contrary, quartz sand ending in slags and afterwards used in construction still holds a function equivalent to that of primary quartz sand in its usual application. In that case quartz sand is considered to hold a "significant function", and is not dissipated (Table 3.1).

Table 3.1 : Examples of dissipative and non-dissipative flows in the LCI of products

	Flows to		
	Environment	Final waste disposal facilities	Products-in-use
Dissipative	Copper emitted to air from a copper smelter	Any metal targeted through an extractive process-chain, ending in waste to final disposal (e.g. copper in copper tailings ponds)	Copper in slags from a copper smelter, used in construction (low function) Any metal non-functionally recycled (e.g. chromium and nickel in special steel recycled in ordinary steel)
Non-dissipative	Copper emitted from coal combustion (copper in coal is not considered a resource) Argon emissions to air	Any metal non-targeted through an extractive process-chain, ending in waste to final disposal (e.g. cadmium in copper tailings ponds)	Quartz sand transferred to slags through copper smelting, and used in construction (significant function)

3.3.3.2 Dissipation to the environment and to final waste disposal facilities

Moreover, here as a more generic rule, any flow to the environment and to final waste disposal facilities can be considered dissipated if (and only if) the corresponding substance enters the unit process as a resource (Table 3.1). However, in some specific cases, such flows of resources to the environment and to final waste disposal facilities may still be accessible to future users in the 25-year timeframe considered (and accordingly, "non-dissipative"). For example, argon, usually produced from the distillation of air, is generally dispersed back to air through its various applications. Such an emission to air can be considered non-dissipative, since the argon is still "accessible to future users" (once back in its original medium, it can be re-extracted with a process similar to the one from which it was initially produced). Moreover, in some specific cases of landfills and tailings disposal facilities, waste may be processed some years later for metal production. This implies that some metals in some final waste disposal facilities may be "accessible to future users" in a 25-year horizon, depending on a number of parameters including technology capacities and market demand. For example, mineral waste deposited in dumps and tailings ponds at the Penouta Mine in Spain, closed in 1985, have been reprocessed since 2018 (i.e. 33 years after closure) in particular for tin, tantalum and niobium productions (Blengini et al., 2019). Also, in some cases of landfills, the recovery of secondary materials, through "Enhanced Landfill Mining", may be a complement to actions of environmental remediation or recovery of the land for other uses (Blengini et al., 2019).

3.3.3.3 Occupation-in-use is not a form of dissipation

Contrarily to the flows of resources to the environment, to final waste disposal facilities and to products-in-use in the technosphere with low functionality, occupation-in-use (also called "borrowing-in-use") of resources in the technosphere is not considered as a dissipation. Indeed, by definition of a resource occupation-in-use, the function(s) that the resources could hold in the technosphere is (are) exploited. Yet, it is acknowledged that, despite not being a form of dissipation, occupation-in-use could be considered as potentially affecting the accessibility of the resources for other users.

3.3.4 Resource Flow Analysis to quantify dissipative flows

The substance flow analysis of resources (called "resource flow analysis" in the following) is the overall concept underlying the suggested approach to account for dissipative flows at the unit process level. It consists in quantifying the flows of resources going through the unit process, entering as resources from ground and resources embodied in products from the technosphere, and coming out either as i) embodied in the output product, in which they can either be conserved (that is, holding a significant function in the product) or, by opposition, dissipated (if holding a low function), ii) directly dissipated as emissions to the environment, and iii) embodied in a waste for further treatment, and subsequent conservation (i.e. significant function conserved, through e.g. a recycling process in the subsequent life cycle step) or dissipation (e.g. through final disposal in a landfill). Resource flow analysis accordingly enables to identify and quantify all the output dissipative flows of resources at the unit process level, in a consistent way (i.e. in a way that fulfills the mass balance equation). In particular, output mineral flows not entering the unit process as resources shall not be classified as dissipative flows of resources, by definition. This implies for example that regarding emissions to the environment, only emissions of resources (i.e., emissions of substances traced in the resource flow analysis as entering the system as resources from ground or as resources embodied in products) are dissipative flows.

3.3.5 Data requirements: potentialities of existing LCI datasets

It is expected that existing LCI databases contain at least part of the data and information required to compile the dissipative flows of resources at the unit process level. Two different situations can essentially be distinguished regarding the "dissipative flows" that need to be added to the LCI datasets:

i) Flows already considered in LCI datasets, but not modelled as "resources dissipated"

This is primarily the case for dissipative flows to the environment, for which the corresponding emissions are reported as elementary flows in existing LCI datasets. However, the following aspects should be considered to account for dissipative flows:

- only resources can be dissipated (as in Table 3.1). Accordingly, one needs first to identify the resources inputs to the unit process under study before classifying the corresponding output emissions as dissipative;
- moreover, some resources are not emitted to the environment "as such". For example, in the mining and metal industry, limestone (primarily calcium carbonate) may be dissipatively used as a reagent and partially emitted to the environment (e.g. as CO_2 to air). In such a case, calcium carbonate is the resource dissipated to the environment. More generally, the dissipative resource flow should not be reported as the substance/compound emitted, but rather as the corresponding resource entering the unit process, whether emitted to the environment under the same form or not;
- finally, the nomenclature should specifically indicate that the corresponding flow is a "dissipative" flow of "resource"; i.e. the current approach for reporting emissions to the environment in LCIs should be complemented.

ii) Flows already considered in the models and supporting documents of existing LCIs

This is the case for waste, products or some emissions (e.g. particulates) which may contain resources potentially dissipated. LCI datasets generally do not provide detailed information on their resource content, but the materials supporting the datasets (e.g. reports or scientific publications) contain a

number of elements that could be reinvested with a view to quantifying the amount of resources dissipated (e.g. regarding the elemental composition of waste).

3.4 Application to a case study: cradle-to-gate production of copper cathodes

3.4.1 General description

The approach described in section 3.3 is applied to analyze the dissipative flows directly generated along the cradle-to-gate primary production of copper cathodes, considering ecoinvent (v3.5) datasets. This case study aims at exemplifying how existing LCI datasets from major LCI databases could be complemented to account for dissipative resource flows, here in the specific case of an extractive activity for which resource elementary flows are currently inventoried as “extracted from ground”.

3.4.2 System boundaries

The functional unit of the study is set as the production of 1 kg of copper cathode. The system boundaries include (Figure 3.2):

- Mining and concentration, which result in the production of copper concentrate (containing around 30% of copper) from sulfidic copper ore extraction and treatment. This activity additionally generates molybdenite, as a co-product whose subsequent life cycle is considered out of the scope of the system boundaries, and sulfidic tailings (waste). In this case study, tailings are considered to be disposed of in a tailings management facility (heaps or ponds), as common practice in the industry (Classen et al., 2009);
- Pyrometallurgy, resulting in the production of copper cathodes from the treatment of copper concentrate. The process also generates iron silicate slags, considered to be used in construction, as common practice in the industry (Cusano et al., 2017).

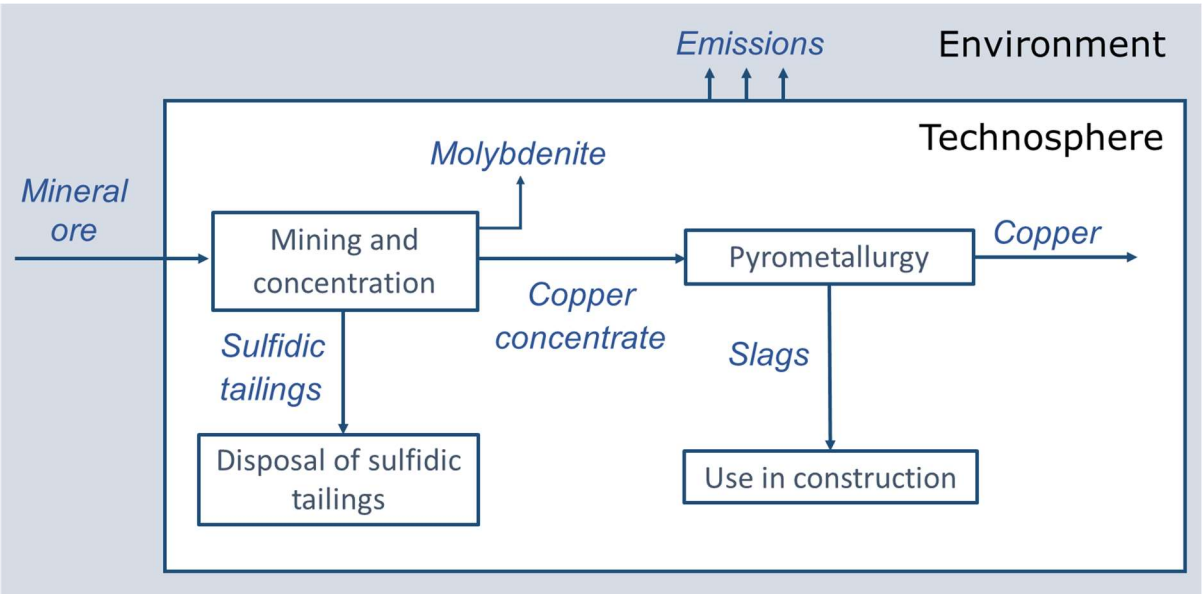


Figure 3.2 : System boundaries for the analysis of the cradle-to-gate primary production of copper

3.4.3 Life Cycle Inventory

This case study mainly builds on the exploitation of two ecoinvent datasets: “copper mine operation, sulfide ore, GLO” and “copper production, primary, GLO”, respectively representing the process of copper concentrate production and copper production (from copper concentrate) at a global scale (ecoinvent, 2021; Classen et al., 2009). The ecoinvent “undefined system model”, corresponding to “the way the datasets are obtained and entered by the data providers”, has been considered in the following (ecoinvent, 2021). The approach firstly consisted in computing a “resource flow analysis” of the two main activities under study (respectively, mining and concentration, and pyrometallurgy), before deriving an inventory of direct dissipative flows per kg of output copper cathode.

3.4.3.1 Resource flow analysis

Firstly the mineral resources entering the two activities have been identified and quantified in mass units. The term “resources” is here understood in its large sense, encompassing both primary resources from ground and resources embodied in intermediate products used as inputs to the activities, as defined in section 3.2.3. It is noteworthy that this step focuses on inputs and outputs of mineral resources, and it does not include inputs of energy carriers. Similarly, the corresponding output flows of mineral resources have been quantified.

In this case study, this resource flow analysis has been performed considering the following hierarchy of data (see Appendix B for a complementary description):

1) data in inventory datasets, essentially regarding elementary flows of emissions (e.g. copper to air) or resources extracted from ground (e.g. copper and molybdenum from ground). Yet these data only partially enabled to perform the resource flow analysis of the activities under study. A number of resource flows (embodied in intermediate products used as inputs to the activities, embodied in output products and embodied in waste) cannot be directly drawn from inventory datasets. Complementary data sources have been used, as detailed in the following steps 2 and 3;

2) background data in the supporting ecoinvent report detailing the inventory compilation, for example regarding the content of copper and molybdenum in copper concentrate and molybdenite (Classen et al., 2009);

3) hypotheses when no other data considered reliable was available in the ecoinvent database (i.e. either in the datasets or in the supporting documentation). In particular, the masses of resources embodied in reagents in mining, concentration and pyrometallurgy, were derived by combining *i)* the mass data present in the ecoinvent dataset and *ii)* complementary information regarding the nature of reagents, considering information as in the supporting ecoinvent report (Classen et al., 2009) and additional assumptions. Moreover, the mass of resources transferred to tailings and slags has been calculated by mass balance, considering the difference between the masses of resources as inputs to and as outputs from the activity. This implies in particular assuming that all the resources in the reagents (e.g. metals in frothers) are transferred to tailings, and not to the output concentrate, which may not reflect the actual situation in the industry. This could be further explored considering additional plant-specific data beyond the ecoinvent dataset used in this study.

Overall, it is noteworthy that this resource flow analysis is key for several purposes. Firstly it enables to correctly identify the resources among the output flows. Only the substances that are identified to be resources entering the activities under study can be classified as dissipative flows of resources. Accordingly, for example, emissions of lead, manganese and mercury to air and water in the activity of mining and concentration are not reported as emissions of resources in the resource flow analysis of the activity. Indeed, these three chemical elements are not entering the activity as resources, neither from ground nor as embodied in intermediate products used as inputs to the activity. In particular they may originate from trace concentrations in the treated ore, not aimed at being extracted from the process (not "targeted metals") and consequently not considered as resources. Moreover, in some cases the emission to environment is accompanied by a change in the form of the substance. For example, limestone is used for pH neutralization in the activity of mining and concentration. It reacts to form emissions (e.g. CO_2) and waste. In this case, the resource flow analysis enables to identify calcium carbonate as the resource entering the process (considering the EF nomenclature of resources) and subsequently dissipated. Finally, in this specific case study on the primary production of copper, this resource flow analysis is key for the estimation of flows of resources to tailings and slags, calculated by using the mass balance equation. More generally, the use of the mass balance equation in the resource flow analysis enables to ensure the consistent mass balance of resources along the cradle-to-gate primary production of copper cathodes.

In the case of the activity of mining and concentration, this resource flow analysis specifically enables to distinguish two main types of resources (Figure 3.3): *i)* resources targeted by the process of extraction (copper and molybdenum), essentially extracted from ground (e.g. copper mainly transferred to the output copper concentrate), and *ii)* resources embodied in products from technosphere, used in the activity, such as reagents and steel for milling, which are not intended to be conserved in the output products (transferred to tailings and environment).

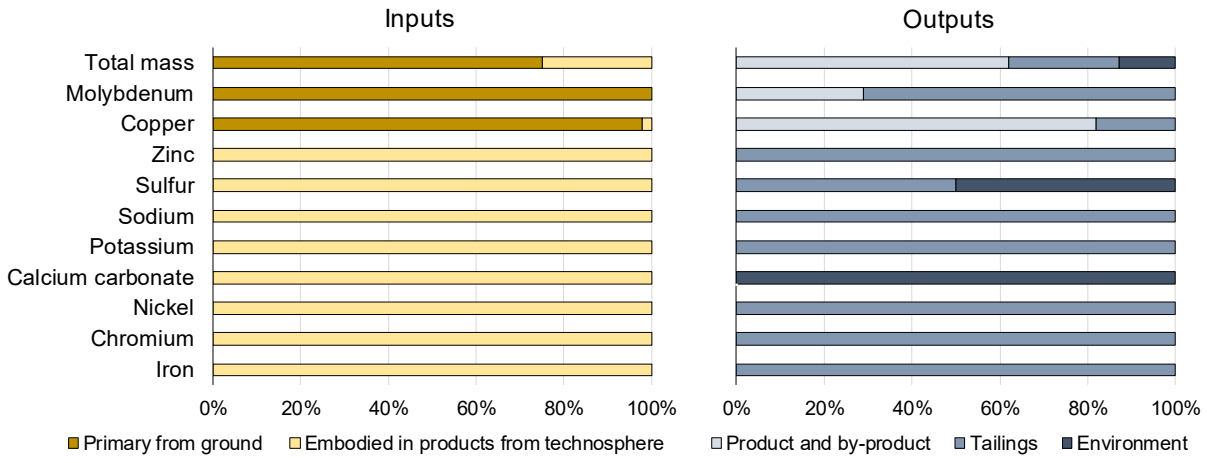


Figure 3.3 : Mining and concentration of a sulfidic copper ore: resources in input and output flows

3.4.3.2 Derivation of dissipative resource flows

The inventory of direct dissipative flows along the cradle to gate production of 1 kg of copper cathodes has been derived from this resource flow analysis (Table 3.2). This step has mainly involved:

- distinguishing the dissipative flows (copper and graphite) from the non-dissipative ones (quartz sand), among the flows of resources in slags used in construction (in that case slag is a "product-in-use" in the technosphere; Table 3.1);
- considering the resource flows to tailings disposal facilities as dissipative. The recovery of critical and other raw materials from extractive waste is not a widely diffused practice in the European Union yet, despite some notable examples (as e.g. reported in section 3.3.3.2) which demonstrate the availability of technologies and the existence of a highly innovative sector (Blengini et al., 2019). It is therefore a reasonable assumption to consider that resources in tailings generated and disposed of along the cradle to gate production of 1 kg of copper cathodes will not be accessible to any future users in a 25-year timeframe, i.e. are dissipated. This assumption is moreover consistent with the modelling of tailings disposal in the ecoinvent database, which does not consider any potential future extraction of their resource content through reprocessing;
- allocating the dissipative resource flows directly generated by mining and concentration (to environment and tailings disposal facility) respectively to copper concentrate and to molybdenite. Economic allocation has been applied as in Classen et al. (2009). This implies that regarding the co-production of 1 kg of copper concentrate and 0.0041 kg of molybdenite, most (99%) of the dissipative resource flows are allocated to the output copper concentrate, while only a limited share (1%) is allocated to molybdenite. It is noteworthy that the allocation procedure could have been implemented in different ways, for example considering updated prices of copper concentrate and molybdenite, potentially completed with a physical allocation approach (e.g. considering the allocation of all primary copper resource dissipated to the copper concentrate). More generally, diverse allocation procedures may be applied to dissipative flows of mineral resources in LCI datasets, as is already the case for other elementary flows such as for example mineral resources extracted from the ecosphere (Berger et al., 2020).

3.4.3.3 Inventory analysis

Overall, in order to produce 1 kg of copper cathode, 0.88 kg of direct dissipative resource flows are generated in the four unit processes (Table 3.2). Tailings disposal (0.37 kg; i.e. representing 42% of the total mass of resources dissipated; Table 3.3), pyrometallurgy (0.25 kg; 29%) and mining and concentration (0.23 kg, 26%) all represent important contributions (in mass terms). Calcium carbonate is the main mineral directly dissipated along the cradle-to-gate production of copper (0.45 kg; i.e. 51% of the total mass dissipated; Table 3.2). Copper also represents a significant contribution (30% in mass terms), while iron (8%), sulfur (5%), molybdenum and chromium (2%) overall represent more limited shares.

Table 3.2 : Cradle to gate production of 1 kg of primary copper: inventory of direct dissipative flows of resources (after economic allocation)

Activity	Type of dissipative resource flow	Amount dissipated	Unit	Share of total mass
Mining and concentration	Dissipation to environment			
	Chromium	5.78E-06	kg	0%
	Copper	4.23E-06	kg	0%
	Calcium carbonate	1.98E-01	kg	22%
	Iron	5.11E-05	kg	0%
	Nickel	8.82E-06	kg	0%
	Sulfur	2.84E-02	kg	3%
	Zinc	2.41E-05	kg	0%
Disposal of sulfidic tailings	Dissipation in tailings disposal facility			
	Chromium	1.65E-02	kg	2%
	Copper	2.30E-01	kg	26%
	Iron	6.79E-02	kg	8%
	Molybdenum	1.92E-02	kg	2%
	Nickel	7.34E-03	kg	1%
	Potassium	5.69E-03	kg	1%
	Sodium	2.04E-03	kg	0%
	Sulfur	1.42E-02	kg	2%
	Zinc	1.15E-02	kg	1%
Pyrometallurgy	Dissipation to environment			
	Copper	2.75E-03	kg	0%
	Calcium carbonate	2.49E-01	kg	28%
Slags use in construction	Dissipation in slags used in construction			
	Copper	2.99E-02	kg	3%
	Carbon (graphite)	1.00E-03	kg	0%
Total		8.84E-01	kg	100%

Finally, in relation with the above results, one observes that 54% is dissipated to the environment, 42% in a disposal facility (disposal of sulfidic tailings), and a much more limited share to a product-in-use (3% in slags used in construction). However, regarding metals only, dissipation to tailings disposal facilities represents by far the largest share (92%), while dissipation to the environment only represents a minor share (1%). In particular, copper (67% of the total mass of metals dissipated) is mainly dissipated to tailings disposal facilities (88%), and to a lower extent in slags used in construction (11%). Similarly, the metals contained in steel used for milling (iron, chromium and nickel; 23% of the total mass of metals dissipated), are essentially dissipated in tailings disposal facilities (Table 3.2 and Appendix B).

Table 3.3 : Share of activities to the total resources and copper direct dissipative flows along the primary production of copper: comparison of short-term perspective (main approach) and long-term perspective (alternative approach)

	Total dissipative flows		Copper dissipative flows	
Activities	Main approach: short-term perspective	Alternative approach: long-term perspective	Main approach: short-term perspective	Alternative approach: long-term perspective
Mining and concentration	26%	47%	0%	0%
Disposal of sulfidic tailings	42%	0%	88%	3%
Pyrometallurgy	29%	52%	1%	95%
Slags use in construction	3%	0%	11%	2%

3.5 Discussion

Primarily considering the results of the case study, this section discusses *i)* how the developed approach would change the interpretation of results regarding mineral resources in LCA (section 3.5.1), *ii)* how far some key methodological aspects of this approach (e.g. the temporal perspective) can affect the inventory results (sections 3.5.2, 3.5.3 and 3.5.4), and finally *iii)* the challenge of potentially incomplete and unbalanced data (section 3.5.5).

3.5.1 From extraction to dissipation: implications on hotspots analysis

The traditional approach to mineral resources in LCI datasets is to account for the resources extracted from the environment (in particular, from ground). Mineral resource flows are primarily reported with respect to extractive activities. The adoption of the dissipation approach implies focusing not only on the early life cycle stages (associated with raw materials extraction), but also on resource functions in later life cycle stages (in which the resources are dissipated through raw material production and manufacturing, use, recovery or final disposal). This has been partially exemplified in this study considering the cradle-to-gate production of copper, for which the operations of tailings disposal and pyrometallurgy both contribute to relatively important shares of the total mass of resources directly dissipated, whereas they have no direct contribution to resource extraction. The contribution analysis based on resource dissipation rather than extraction implies the identification of different hotspot processes in the cradle-to-gate production of copper, and subsequently potentially different hotspots in terms of stakeholders (different companies) and location (different plants, potentially in different countries).

Moreover this shift in hotspots may be accompanied by a transfer of the resource issue from the background system to the foreground system, where the producer or user of the system under study has decisive influence. For example, regarding calcium carbonate in the cradle-to-gate production of copper, the corresponding concern is identified to be in the foreground in the dissipation approach (dissipative use in concentration and pyrometallurgy). This differs from the extraction approach that would identify the upstream supply chain steps of extraction of calcium carbonate as the hotspot stages.

3.5.2 Temporal perspective

The temporal perspective considered to assess resource dissipation should be defined by LCA practitioners when setting the goal and scope of their study. The approach developed in this article is adapted for users interested in a rather short-term perspective (i.e. 25 years). If rather considering a long-term perspective (e.g. hundreds of years), emissions to the environment may be assumed to be the only flows of resources "not accessible to future users" (i.e. dissipative). Instead, any flow to a final waste disposal facility or recovered with low functionality may be assumed to be, at some point in time, accessible to some future users (i.e. non-dissipative) thanks to e.g. landfill mining and tailings reprocessing.

Regarding the case of primary copper production, this long-term perspective would firstly imply that flows to tailings disposal facilities and slags used in construction are not entirely dissipative. Only the emissions to the environment that they generate may be considered to be dissipative, assuming that instead the rest is "accessible to future users" thanks to potential future reprocessing. In order to assess how far this would affect the results and their interpretation, the emissions induced by tailings disposal are calculated by multiplying the masses of resources in tailings by the transfer coefficients associated with tailings disposal in a 100-year-perspective (as considered in the ecoinvent database to express the share of chemical elements in tailings emitted to the environment through leaching; Doka, 2008). Similarly, the transfer coefficients (expressing the share of chemical elements emitted to the environment) for slags disposal in landfills are considered as a proxy to estimate the emissions associated with slags used in construction (Doka, 2009).

This long-term perspective implies a significant shift in main contributions at the level of both unit processes and resource inventory flows (see Table 3.3 which illustrates the different contributions of activities to the direct dissipative flows of resources, when different temporal perspectives are adopted). Pyrometallurgy and mining and concentration are identified as the main process steps (respectively 52% and 47% of the total mass dissipated), with calcium carbonate by far the main contributing resource (93% of the total mass, compared to 51% in the short-term perspective). On the contrary, tailings disposal and slags use in construction show very limited contributions in mass terms (less than 1%). Moreover, copper represents less than 1% of the total mass of resources dissipated, compared to 30% in the short-term perspective, with pyrometallurgy the main process step (95% of the total copper dissipated compared to 1% in the short-term perspective; Table 3.3). Indeed, in the short-term perspective, a relatively large amount of copper is considered to be dissipated in tailings final disposal facilities (2.30×10^{-1} kg) compared to the amount dissipated in the step of pyrometallurgy (2.75×10^{-3} kg as direct emissions to the environment along the process operations; Table 3.2). Instead, in the long-term perspective, copper in tailings disposal facilities is considered to be accessible to some future users (i.e. non-dissipative) at some point in time thanks to tailings reprocessing, except the share emitted to the environment over time (7.7×10^{-5} kg). In the meantime, the amount of copper considered to be dissipated in the step of pyrometallurgy is identical both in the short-term and in the long-term perspectives (2.75×10^{-3} kg).

3.5.3 Compartments of dissipation

The proposed approach distinguishes three main compartments of dissipation (environment, final waste disposal facilities and products-in-use in the technosphere in which the resource provides a low function), implying the distinction of 3 x R dissipative flows (considering that R mineral resources are distinguished in the LCI framework). These three compartments can be subdivided further into S sub-compartments, as for example additionally considered in the application to the case study ("tailings in

disposal facility" and "slags used in construction" considered as sub-compartments respectively of "final waste disposal facilities" and of "products-in-use in the technosphere").

As a complement, further disaggregation could for example consist in differentiating several types of landfills as a function of the waste categories disposed of, several types of tailings to disposal facilities as a function of the ore mined, etc. This differentiation between sub-compartments in particular appears of interest *i)* in an accounting perspective (when building the inventory, it helps to generate a comprehensive set of dissipative flows); and *ii)* in the results interpretation step, offering possibilities to analyze the contributions of each compartment of dissipation regarding the impacts associated with resource dissipation, therefore helping to prioritize actions to limit resource dissipation in the life cycle of the product under study. The need to differentiate between specific additional sub-compartments of dissipation (and by opposition, of non-dissipation) may be additionally identified in future developments of the approach, for example through the potential introduction of additional criteria to quantify the actual dissipation of resources in each compartment (e.g. concentration of metals).

The coupling of resources to compartments (or sub-compartments) may in particular depend on the temporal perspective considered. For example, in the short-term perspective in this study, three compartments and sub-compartments are distinguished: environment, tailings in disposal facility and slags used in construction (Table 3.2). Instead, in the long-term perspective, only the environment may be considered a compartment of dissipation (see section 3.5.2). Moreover, it is noteworthy that the distinction of additional sub-compartments may be accompanied by the distinction between some resources dissipated and some not, as a function of the sub-compartment; i.e. with a total number of dissipative flows inferior to R (resources) X S (sub-compartments). This may particularly be the case for temporal perspectives in-between short- and long-terms, which may require including considerations on potential future reprocessing of tailings or future landfill mining for some mineral resources (see section 3.3.3.2).

3.5.4 Low-functional recovery

The developed approach does not provide any clear-cut rule regarding what should be considered resources with "low functionality", as opposed to resources with "significant" value in products-in-use. Accordingly, despite applicable in the case study (Table 3.1 and Table 3.2), the classification as dissipative in products-in-use may be less straightforward regarding other applications. Additional developments and further research are therefore necessary to define and account more precisely for the actual low-functional recovery and subsequent dissipation of resources in products-in-use, e.g. considering criteria and thresholds. These developments may build on existing approaches implemented in LCA, which consider the quality of materials to account for the benefits of recycling (e.g. in the Circular Footprint Formula of the PEF/OEF; Zampori and Pant, 2019).

3.5.5 (Un)balanced resource flows

In the case study, the resource flows transferred to the tailings have been calculated by difference, using the mass balance equation and available data on inputs and outputs. Another option would have been to use the data supporting the ecoinvent dataset relative to tailings management in a disposal facility (provided by Doka, 2008), which consider a global average sulfidic tailings composition, based on literature data mainly from copper, zinc, lead, nickel and molybdenum mining sites (Doka, 2008). However, considering these data would have implied inconsistent mass balances for the resources under study; e.g. regarding copper for which the mass in tailings would have been 2.5 times lower than the value obtained by mass balance. Indeed, whereas the mass balance calculation implemented in

this study considers the copper content in the ore and the process efficiency (and corresponding transfer to tailings) as modelled in the ecoinvent dataset "copper mine operation, sulfide ore, GLO", the ecoinvent dataset relative to tailings management on the contrary considers an average tailings composition, generated by the extraction and processing of diverse ores (not only copper ores but also other metallic ores, with potentially very diverse contents in copper).

Generally, it is expected that resource flows are well traced in the mining and metal activities. Metallurgical accounting is a common practice to quantify the performances of production plants, in particular regarding metal recovery and losses which drive the economic balance of the plant and for which the use of data reconciliation method and tools appears as best practice (e.g. Brochot and Durance, 2012). The implementation of the dissipation concept in LCIs could take advantage of such existing "resource flow analyses". On the contrary, in many other types of activities, such analysis of flows may be lacking. In such cases, the whole set of available data may be used, and *i)* if complete, being improved by reconciliation techniques, and *ii)* if incomplete, being complemented by using the mass balance equation, as done in the above case study regarding the copper tailings and slags compositions.

3.6 Conclusions and perspectives

This chapter proposes an approach to account for mineral resource dissipation along the life cycle of a product. Considering a short-term perspective (25 years), any flow of resources to i) environment, ii) final waste disposal facilities and iii) products-in-use in the technosphere (with low functionality) is suggested to be reported as dissipative at the level of unit processes. This approach provides a different perspective to the resource issue as classically considered in LCA, in which primary resource extraction is usually under focus. Accounting for resource dissipation in LCIs implies partly transferring the resource focus from the extraction stage to stages later in the life cycle (resource dissipation through raw material production and manufacturing, use, recovery or final disposal). Therefore, this approach appears well adapted to identify potential improvements on life cycle stages for which the producer or user of the system under study has decisive influence. It may accordingly be particularly relevant to better support the development of more resource-efficient techniques or product designs. However, the transfer of the resource focus from the extraction stage to stages later in the life cycle has only been partially explored in this cradle-to-gate case study. The accounting of resources dissipated rather than resources extracted implies transferring the focus from copper mining and concentration to the disposal of tailings, pyrometallurgy and subsequent slags management. This calls for additional case studies considering the full life cycle of products and systems, in order to explore further resource dissipation in the use, recovery and final disposal phases of these products and systems.

Such a significant change in the perspective adopted to approach the issue of mineral resources in LCA would necessarily imply significant changes in LCI datasets, mainly in terms of a significant adjunction of new flows. As demonstrated in this study in the case of ecoinvent data for copper production, it is expected that existing LCI datasets and supporting documentation contain at least part of the data and information required to compile the dissipative flows of resources at the unit process level. Moreover, the developed approach could also take advantage of current practices in some industries, in which resource flow analysis is a common practice with respect to process control, development and optimization, from lab to industrial scales. In parallel, novel aspects such as a precise definition and accounting of low-functional recovery will also require further research.

Finally, such a significant change in the perspective regarding the resource issue in LCA also implies the need for an adapted impact assessment method, in order to account for the impact actually induced by the dissipative flows of resources. Such method development appears a major requirement for any potential future routine implementation of the concept of resource dissipation in LCA. This is explored in the following Chapter 4.

4 Chapter 4 – The JRC price-based Life Cycle Impact Assessment method

This Chapter is essentially[1] drawn from:

Ardente, F., Beylot, A., Zampori, L., 2023. A price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value. The International Journal of Life Cycle Assessment 28, 95–109. https://doi.org/10.1007/s11367-022-02102-4

Contribution of the co-authors:

- Fulvio Ardente: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.
- Antoine Beylot: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.
- Luca Zampori: Conceptualization, Methodology, Investigation, Writing – original draft, Writing - review & editing, Visualization.

[1] as the main difference between this version (in this Chapter) and the version in the article (Ardente et al., 2023): the approach to calculate the normalization factor explored at the EU level in Ardente et al. (2023) is not reported in this Chapter

4.1 Introduction

As presented in Chapter 3, the Joint Research Centre of the European Commission developed a Life Cycle Inventory method, called JRC-LCI method. It relies on accounting for dissipative flows at the unit process level in LCI datasets, considering a short-term perspective. Tested on a case study, this method proved relevant to identify hotspots in terms of resource dissipation in supply chains, in mass units. Yet, so far, this method stands for a "fate model" enabling to distinguish between dissipative and non-dissipative resource flows at the unit process level, while the "effect" induced by these dissipative flows is not assessed.

The TF mineral resources of the UNEP Life Cycle Initiative hosted by UN Environment stated that the damage to the safeguard subject for "mineral resources" is the reduction or loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere (Berger et al., 2020). In this context, this chapter complements the JRC-LCI method, which so far enables to account for dissipative flows in a product system at the LCI level in mass units (Beylot et al., 2021; Chapter 3), with an impact assessment method that further quantifies the damage induced by these dissipative flows. The combination of the JRC method, at the LCI level (Chapter 3) and at the impact assessment level (this Chapter 4), eventually enables to quantify reduced accessibility to mineral resources value in LCA.

This chapter is structured as follows: section 4.2 describes the proposed method (including impact pathway description and computation of CFs); section 4.3 presents the resulting CFs and impact assessment in a case-study; section 4.4 discusses these results in terms of i) the new insights this method brings as support to decision-making, ii) sensitivity to the timeframe considered for CFs calculation, iii) possible approach for defining normalisation factor; and iv) relevance, robustness, completeness, and consistency of the method.

4.2 Method

4.2.1 Impact pathway description

4.2.1.1 "Value": the key concept to be captured in the damage assessment

The TF mineral resources defined the safeguard subject for "mineral resources" with the intention to account for "humans as the most relevant stakeholders for mineral resources, i.e., the focus is on the instrumental value of resources for humans" (Berger et al., 2020). "Value", or "utility" (i.e. by providing a certain function) for a certain subject (usually humans, in the common anthropogenic perspective) is more generally classically core in the definition of natural resources in the literature (Ardente et al., 2019). Value was moreover key in the intended consensus process as described for the SUPRIM project by Schulze et al. (2020a), which concluded that the so-called type B perspective ("Abiotic resources are valued by humans for their functions used (by humans) in the technosphere") best summarized their view on the role of abiotic resources. Still at this stage, there is no consensus on the way either the resource value (potentially "instrumental") or the "potential to make use of the value that mineral resources can hold for humans in the technosphere" (Berger et al., 2020), shall be captured, in particular in LCA. Capturing value in the quantification of the damage to mineral resources in LCA is moreover also in line with principles of circular economy, as e.g. fostered in the EU action plan for the circular economy (EC, 2015). In the latter, the instrumental value/function of the natural resources (extracted, harvested and overall transformed) are aimed to be maintained for beneficial use by humans.

4.2.1.2 Accounting for mineral resource dissipation and induced value loss in LCA

In this context, this study suggests the following impact pathway to account for the reduction or loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere. A product system requires the use ("consumption") of mineral resources. Part of these are extracted from ground (primary resources), while the remaining share stems from the life cycle of other product systems via recycling activities (secondary resources). It is noteworthy that:

- The concept of "resources" as intended here matches the understanding by the TF mineral resources, which encompasses resources from both ecosphere and technosphere. It also aligns with the perspective promoted by Schulze et al. (2020a), according to which "resources may originate from both primary and secondary production";
- "resources" here refers to the ones used by the product system, not to the geological stock of resources as sometimes implicitly considered when referring to "resource depletion".

All along the life cycle of the product system under study, part of these resources are rendered not accessible to future users due to different constraints, which prevent humans to make use of the function(s) that these resources could have in the technosphere (e.g. mineral resources emitted to environment). Building on the definition of "resource dissipation" provided by Beylot et al. (2020b), as presented in Chapter 2, the product system under study consumes/uses mineral resources as inputs, and delivers part of these mineral resources in a dissipated form. It is noteworthy that the level of accessibility of (potentially) dissipative mineral resources may depend on technological and economic factors, which can change over time (Beylot et al., 2020b). The temporal perspective is therefore key in the determination of dissipative flows and shall be specified in any method development building on this impact pathway.

Subsequently, these dissipative flows (or losses; Beylot et al., 2020b) of mineral resources further imply the loss of the value that these resources can hold for humans in the technosphere, as humans cannot access them anymore within the time horizon in the problem definition. These dissipative flows damage the safeguard subject for "mineral resources" in terms of a loss of value. Any method that is developed following this impact pathway is accordingly expected to address the question: "*How can I quantify the consequences of temporal or permanent loss of the functional values of natural resources (as related to dissipation) caused by its use in a product system?*".

4.2.1.3 Resource prices as a representative proxy for resource value

Mineral resources hold a value regarding what they can be used for by humans, i.e. in terms of "services" they may provide to humans within a product (either alone or in combination with other mineral — and sometimes non-mineral — resources). This can reflect an anthropocentric perspective focused on the role of resources in the economy (Schulze et al., 2020a). For example, the use of tungsten allows mobile phones to vibrate, while gallium and indium are part of light-emitting diode technology in lamps. This "value" is therefore highly connected to the function(s) that the mineral resources may provide to humans, so that the term functional (or instrumental) value may sometimes be used instead of "value".

The market price of mineral resources represents the way that these resources are valued by the economic actors requiring their use for product manufacturing (e.g. electronics, automotive, building, etc. sectors). Higher priced metals (e.g. tungsten, gallium and indium) are generally used in more specialized applications than cheaper ones, for which their specific functionalities can be fully utilized. Despite these natural resources may also provide some more basic functions, their high production

cost normally prevents their use in lower added-value applications for which they are substituted by lower priced resources.

Metal price variations and their consequences in terms of substitution highlight further the close connection between function, value and price of mineral resources. Resource prices also reflect their availability in the market (in a certain moment), as also affected by geopolitical tensions and social aspects: prices are affected by (and to some extent, reflect the) competition between different production processes. In case of higher prices of metals, the latter are used specifically for some of their higher-valued functionalities, e.g. copper substituted by aluminium for pipes or electrical applications when the price of copper increased in the 2000s. In that case, the increase in copper price led to its use preferentially in applications of higher value. We may conclude that market prices of resources may be influenced by a large number of factors (some of them as listed above), being, however, a discussion of how prices are determined beyond the scope of this article.

The use of economic relations is also not new in LCA: for instance, the use of allocation factors based on the economic value of different co-products can summarize complex attributes of products or services quality that cannot be easily measured by physical criteria (Ardente and Cellura, 2012).

Overall, the general assumption and concept behind the proposed method for building CFs for resources is that price can be considered a proxy for the multiple, complex and varied functions and values that natural resources can have in highly interconnected socioeconomic systems. It is recognized that natural resources could have cultural, spiritual or emblematic "values" that could not be captured by the economic value (Dewulf et al., 2015); still, we consider that price-based CFs can be a good proxy of the overall resource functions and values[2], especially for short-term evaluations[3] with the additional benefit that these are easy to be calculated.

As a concluding remark on this section 4.2.1, it is noteworthy that this general impact pathway is further discussed and elaborated in the following Chapter 5, section 5.2.2 – in particular with a graphical representation in Figure 5.1.

4.2.2 Impact assessment and associated characterization factors: operationalization

This section describes the operationalization of the above-presented general impact pathway. Dissipative flows of mineral resources are accounted at the LCI level through implementation of the JRC-LCI method (as presented in Chapter 3). The associated value lost is assessed through a market-price-based method as described in sections 4.2.2.1 and 4.2.2.2.

4.2.2.1 Damage assessment

The impact of resource dissipation in terms of value loss can be calculated as the sum of the mass of each individual resource dissipated multiplied by a CF that reflects its value with respect to a reference substance (Eq. 1):

Equation 1: $Value\ Loss\ (VL) = \sum_{i=1}^{n} m_i \cdot CF_i$

[2] For a comprehensive discussion on value and functions of resources, we recommend dedicated articles on the subjects, as in Dewulf et al. (2015) and Schulze et al. (2020a)

[3] Different and better proxies could be used in long-term assessments, although the authors consider that, due to their simplicity, long historical series of market prices may be also considered for assessments referred to longer time frames.

Where:

- Value Loss (VL) = impact related to dissipation of mineral resources value [kg Ref. Sub. $_{€eq.}$]
- m_i = mass of the i^{th} mineral resource dissipated [kg];
- CF_i = characterization factor of the i^{th} resource, compared to a reference substance and calculated as in Eq. (2):

Equation 2: $$CF_i = \frac{Price_{Av,i}}{Price_{Av,ref.sub.}} = \left[\frac{\frac{€}{kg_i}}{\frac{€}{kg_{Ref.Sub.}}}\right]$$

Where:

- $Price_{Av,i}$ = average price (over a certain timeframe) of the i^{th} resource [€/kg];
- $Price_{Av,ref.\ sub.}$ = average price (over a certain timeframe) of a reference substance [€/kg].

This method delivers the impact of a product system on the safeguard subject "mineral resources" in terms of "Value Loss" (VL), i.e. in terms of the loss of value that mineral resources can hold for humans in the technosphere. The approach proposed in equations 1 and 2 is relevant for assessment in a short-term perspective, although it might be relevant also for longer temporal scopes, especially in the absence of easy and suitable alternatives. Through this method, all the flows of different resources dissipated accounted for in the LCI phase (e.g. copper, aluminium and iron) are translated in the equivalent dissipated mass of a reference resource (e.g. copper, gold or antimony) based on their relative values. For example, assuming copper as reference substance, an hypothetical impact of VL equal to 2.5 kg $Cu_{€eq}$ would mean that, along the whole life cycle of the system under study, the overall amount of all the resources dissipated is equivalent, in value terms, to 2.5 kg of copper.

4.2.2.2 Price data for characterization factors determination

The Historical Statistics for Mineral and Material Commodities of the United States Geological Survey (USGS) are considered in this study for implementation of equations 1 and 2 (USGS, 2020). They represent a comprehensive database for resources' prices, characterized by good data availability (relatively high completeness), precision, representativeness and with up-to-date information. Net present value (which is the economic function that allows to compare cash flows occurring in different times) is considered in order to account for the time value of money.

Prices of resources can be affected by variability, especially in short timeframes, induced by a multitude of aspects not necessarily related to the utility of the resource (e.g. political decisions, wars and tariffs), and beyond the scope and problem definition of this article. However, when considering longer periods (e.g. some decades), price fluctuations of many resources tend to be less important. One main temporal perspective (50 years) is considered, with four additional temporal perspectives (10, 15, 20 and 30 years) considered within a sensitivity analysis (see Appendix C).

4.2.2.3 Scope of the impact assessment method

The resource scope, temporal scope and geographical scope of this price-based impact assessment method may be reported with building on the framework developed by Schulze et al. (2020a). In this study, price-based CFs are developed considering elements (e.g. copper and zinc) and configurations (e.g. clays and gypsum). They may be applied with LCI accounting for either dissipative flows or flows extracted from ground, at the elemental and configurations level as in the JRC-LCI method (for

dissipative flows) or standard LCI databases (for resource flows extracted from ground). The five temporal perspectives (10, 15, 20, 30 and 50 years; with 50 years as the main reference) are all rather short-term perspectives. This temporal scope of the price-based CFs makes them particularly fit for combination with the JRC-LCI method in a short-term perspective (25 years), as developed in Chapter 3 (Beylot et al., 2020a; 2021). Still, the proposed price-based approach might be relevant to be used for longer perspectives, but this requiring additional investigation. Finally, the developed method enables to address the mineral resource issue on a global scale, yet with potentially some differences in values (prices) depending on the region of the world where losses actually occur (see the section 4.4 where potential need for regionalization is addressed).

4.2.3 Case study

This method to account for resource value loss in LCA is tested on one case study. The latter builds on Chapter 3 (Beylot et al., 2021) which assessed direct dissipation of mineral resources along the cradle-to-gate primary production of copper, with 1 kg of copper cathode as the reference flow. Beylot et al. (2021) accounted for the mass of dissipative flows along the production process steps. In this Chapter, the damage induced by these dissipative flows is further assessed. The system boundary first encompasses mining and concentration, which result in the production of copper concentrate (containing around 30% of copper) from sulfidic copper ore extraction and treatment. In this case study, tailings are considered to be disposed of in a tailings management facility. The copper concentrate is then further treated in pyrometallurgy, resulting in the production of copper cathodes from the treatment of copper concentrate. This case study mainly builds on the exploitation of two ecoinvent (version 3.5) datasets: "copper mine operation, sulphide ore, GLO" and "copper production, primary, GLO", respectively representing the process of copper concentrate production and copper production (from copper concentrate) at a global scale (ecoinvent, 2021; Classen et al., 2009).

It is highlighted that this case-study has been discussed to analyse the applicability of the proposed method, although further testing of full cradle-to-grave examples would provide further relevant insights regarding dissipation in the use and product end-of-life phases of products and systems life-cycles – as explored in the following Chapter 5.

4.3 Results

4.3.1 Characterization factors

The CFs are computed for 66 minerals and chemical elements based on their 50-year price-average, considering copper as the reference mineral resource. They are represented in Figure 4.1 and Figure 4.2 distinguishing four categories of metals as defined by the UNEP (2011; precious, specialty, ferrous and non-ferrous metals), in addition to one generic category of minerals. For sake of clarity, CFs have been represented in two separate figures, distinguishing resources with CFs > 1 from those with CFs < 1. CFs are available in Appendix C, considering alternative timeframes (10, 15, 20 and 30 years, in addition to 50 years) and different reference substances (e.g. gold and antimony, in addition to copper). Highest CFs are observed for precious metals (gold, platinum group metals — PGMs — and to a slightly lower extent silver; Figure 4.1). Precious metals have historically been prized for their relation to wealth and status, but they are increasingly used in technological applications (UNEP, 2011). The CFs associated with gold and PGMs are more than three orders of magnitude larger than that of Cu, by definition set to 1 in this method as the reference chemical element. Moreover, specialty metals

are also globally highly ranked in this classification (Figure 4.1). They are classically used in industrial and consumer products in small amounts thanks to their specific chemical and physical properties. Rhenium, thallium, gallium, germanium, etc. in particular have CFs between 2 and 3 orders of magnitude larger than that of copper. Thirdly, ferrous and non-ferrous metals have CFs in-between one order of magnitude larger and one order of magnitude lower than that of copper. In particular, the basic metals lead, nickel, tin, aluminium and zinc are ranked relatively close to copper. Finally, minerals are globally ranked in the second part (and bottom) of this hierarchy (Figure 4.2). These minerals include in particular gypsum, feldspar, diatomite, salt, sand and gravel, etc.

Figure 4.1 : Price-based CFs for mineral resources value loss accounting: only positive values in logarithmic scale are represented (i.e. CFs > 1 [kg $Cu_{€\,eq}$/kg]); considering Cu as reference substance and 50 year-price average

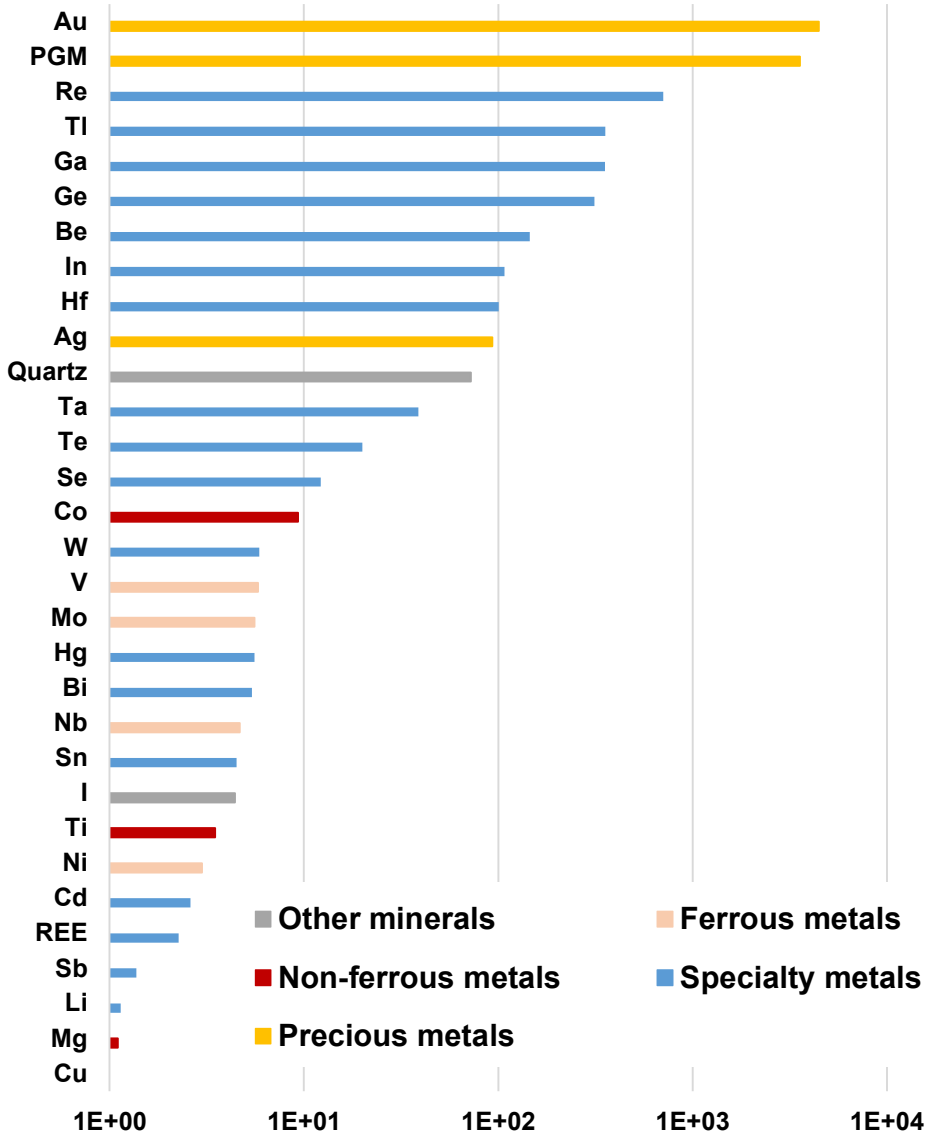
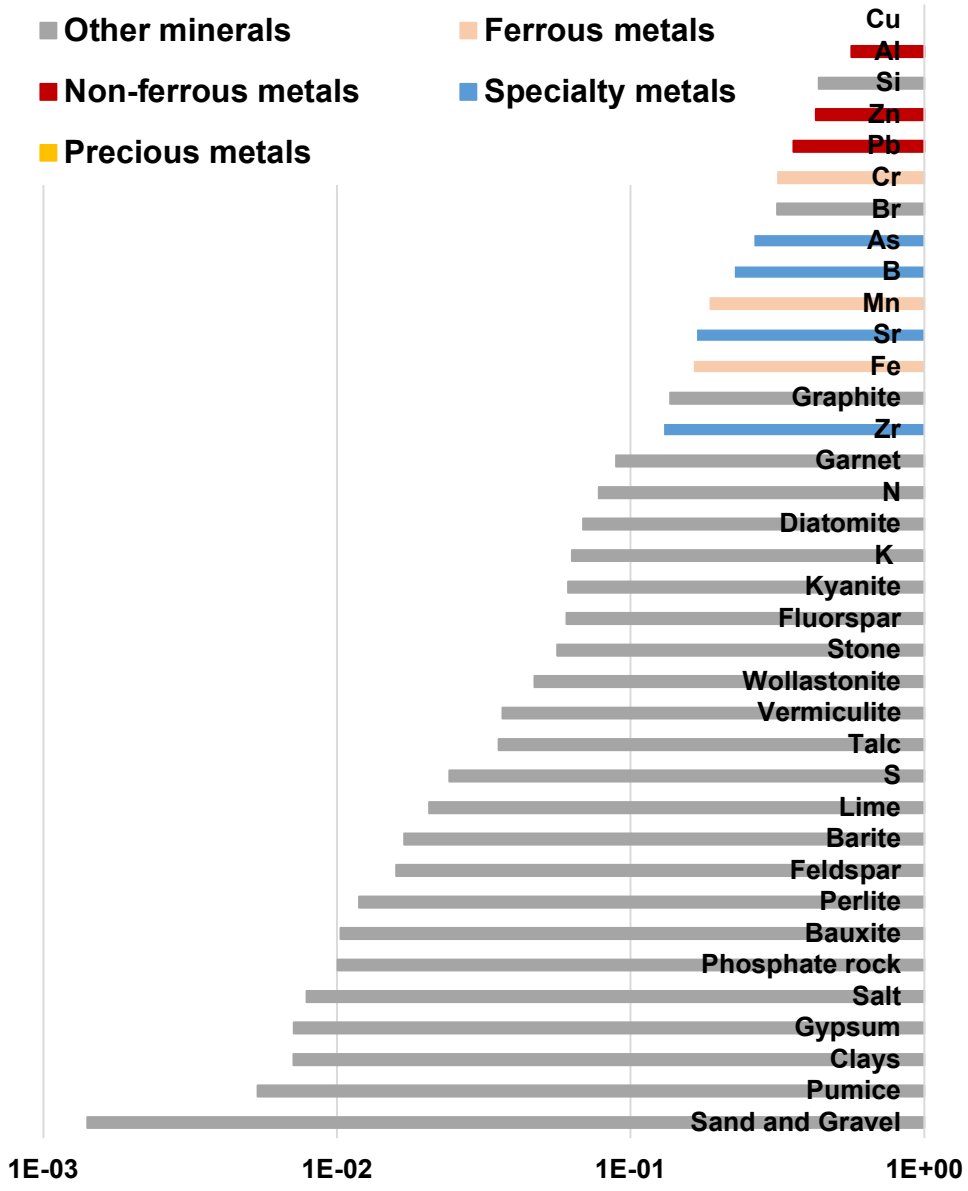


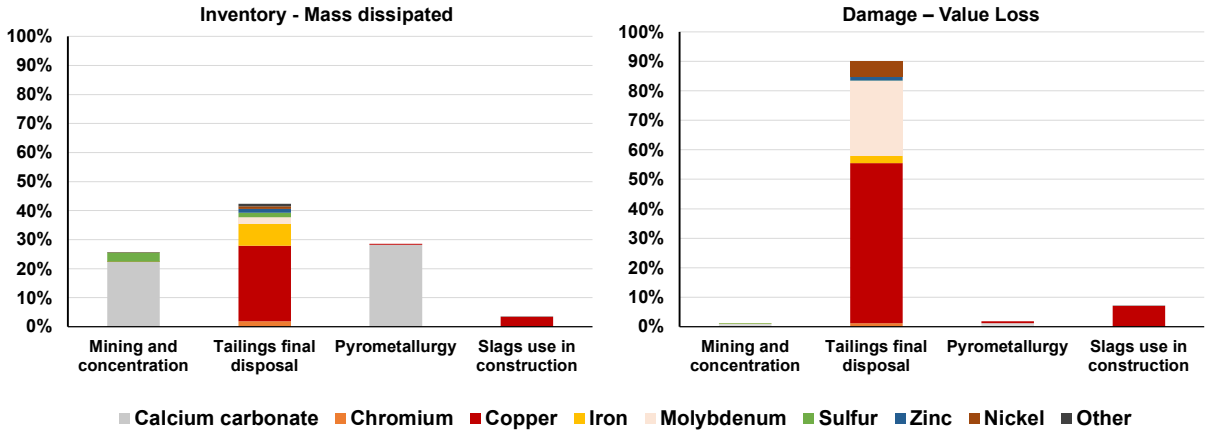
Figure 4.2 : Price-based CFs for mineral resources value loss accounting: only negative values in logarithmic scale are represented (i.e. CFs < 1 [kg Cu $_{€ eq}$/kg]); considering Cu as reference substance and 50 year-price average



4.3.2 Application to a case study

Dissipative flows of mineral resources are accounted at the LCI level, based on the JRC-LCI method, as already presented in Chapter 3 (Beylot et al., 2021), including the discussion on main assumptions and limitations. In order to produce 1 kg of copper cathode, 0.88 kg of direct dissipative resource flows is generated, mainly in the form of calcium carbonate (51% of the total mass) with copper additionally representing a significant contribution (30% in mass terms), while iron (8%), sulphur (5%), molybdenum and chromium (2%) overall represent more limited shares (Figure 4.3). Tailings final disposal, and to a slightly lower extent pyrometallurgy and mining and concentration, all represent important contributions in mass terms (respectively 42%, 29% and 26%).

Figure 4.3 : Contributions of dissipative flows to the total mass dissipated and damage on mineral resources value, induced by copper production



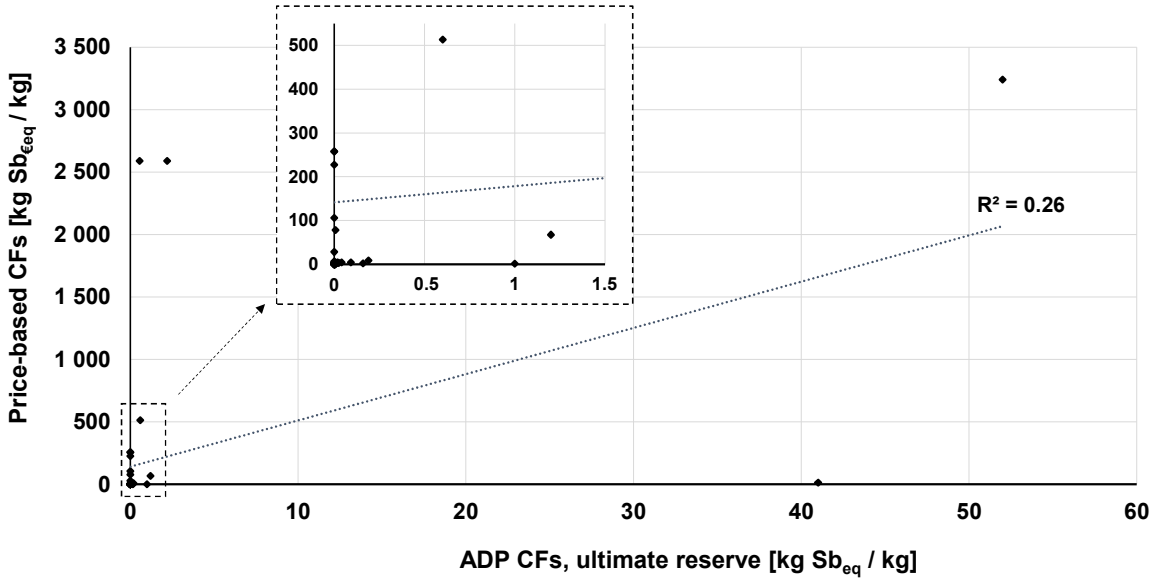
The further implementation of market price-based CFs as developed in this study, applied to the dissipative flows at the unit process level, enables to account for the associated resources value loss. Copper is the main contributing mineral and metal resource, representing 62% of the total impact. Mineral resource value loss is mainly associated with copper loss in tailings disposal facility (54%), and to a lower extent in slags used in construction (7%) and in environment (1%). Molybdenum is the second most contributing resource (25%, in tailings disposal facility). Other dissipative resource flows have more limited contributions (nickel, 5%; iron, 3%; calcium carbonate, 2%; etc.), as driven by smaller masses dissipated compared to copper and molybdenum (e.g. in the case of nickel) and/or due to lower CFs (e.g. regarding iron and calcium carbonate). Tailings final disposal is the hotspot process step, representing 90% of the damage to mineral resources value. Instead, dissipation as emissions to the environment (from mining and concentration and pyrometallurgy) only represents 3% of the total damage to mineral resources value.

4.4 Discussion

4.4.1 Comparison with depletion-based impact assessment method

Price-based CFs may be put in perspective with abiotic depletion potential (ADP) CFs, ultimate reserve, as recommended respectively by the TF mineral resources and by the European Commission in the PEF method, to calculate the contribution of mineral and metal resource use to depletion (EC, 2021). Prices and ultimate reserves capture two distinct aspects of mineral resources, respectively value and scarcity, only poorly interconnected and eventually resulting in very different sets of CFs, as demonstrated by a poor correlation ($R^2 = 0.26$; Figure 4.4). For example, ADP CFs for gallium and germanium are very low (order of magnitude of 10^{-7}) because they are not scarce in the Earth's crust. Instead their CFs based on prices are relatively high (beyond 200): the amount of these resources available in the market for practical uses is relatively low compared to demand in several very specific, high-valued, applications. Actually, a resource may be largely present in the crust (as magnesium, one of the most abundant element in Earth's crust and marine water), but still the resource can be scarce in forms that can be mined and made available for the production processes (e.g. magnesium listed among the EU Critical Raw Materials list; EC, 2020). The proposed method therefore may be more relevant for assessment in a short-term perspective, focusing on the use of the resources in the technosphere (as currently known).

Figure 4.4 : Price-based CFs (average 50 years) as a function of ADP CFs (ultimate reserve), considering 45 chemical elements and with Sb as reference substance in both cases



4.4.2 Timeframe and price variations

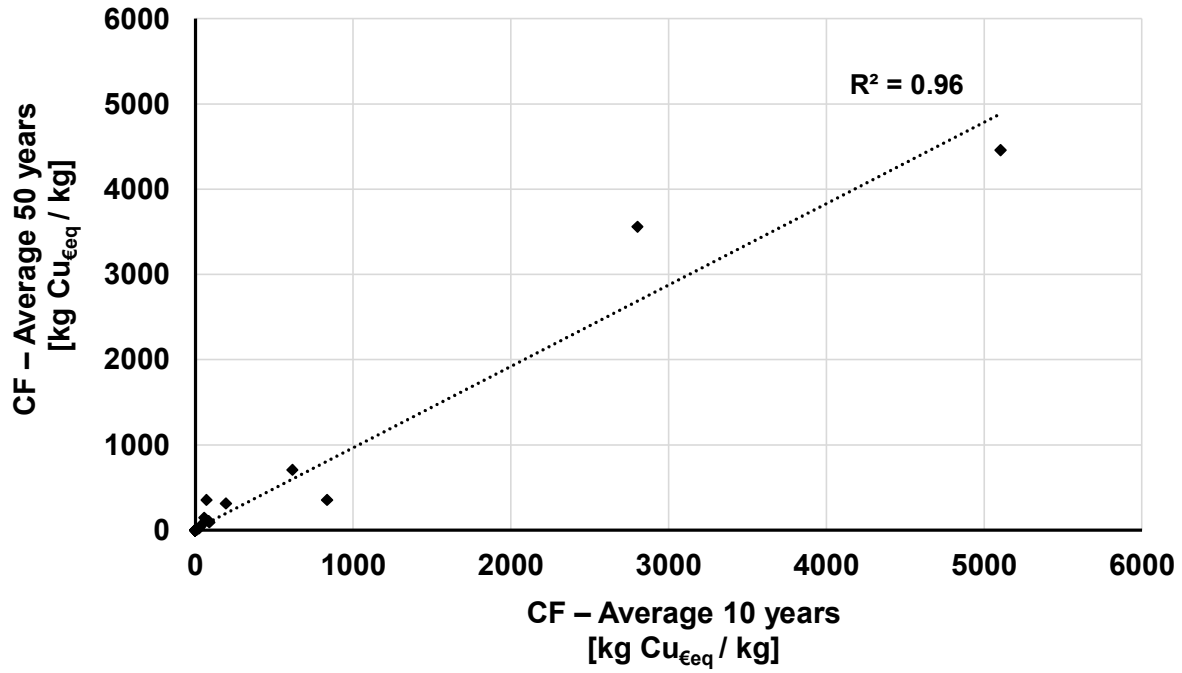
Metal prices are known to be relatively volatile. This is for example the case for rare earth elements, whose prices have significantly increased in 2011, e.g. by a factor 70 for neodymium considering its value in July 2011 compared to the period 2002–2003, in average (Bru et al., 2015). Despite their volatility, in a very common context of metal co-production (i.e. multi-functional) processes, metal prices have classically been considered in LCA as an allocation key to assess the impacts by co-produced metals. For example, in their LCA study applied to metal production, including rare earth oxides, Nuss and Eckelman (2014) consider average prices over the period 2006–2010. Arshi et al. (2018) instead consider prices for rare earths in 2016. The choice for different short-time intervals to calculate price averages as allocation keys, in particular in the context of rare-earths elements which showed very extreme price increase in 2011, may partly drive different impact assessment results as obtained in different studies.

Building on this observation, in this study, the timeframe for deriving average prices has been intentionally set to a relatively long period (50 years). Such time interval is particularly adapted to smooth out prices fluctuations and prevent that sudden, short-term, effects of volatility have large effects on the determination of the average price. It is also assumed that the relative differences in prices between resources may be considered a proxy for the price differences between resources in the short-term future.

The influence of the chosen timeframe set to calculate price-based CFs is further investigated in a sensitivity analysis considering average prices over 10, 15, 20 and 30 years, as compared to 50 years set as the reference in this study. Sixty mineral resources are covered in this sensitivity analysis, compared to 66 covered with a CF for the 50-year timeframe. This is due to lack of recent data which hampers to calculate reliable CFs for shorter timeframes. Despite differences between CFs of different resources calculated respectively for a 50-year timeframe and for 10, 15, 20 and 30 years, one observes a very good correlation, as demonstrated by R^2 in the interval [0.96; 0.99] (Figure 4.5 and Appendix C). Despite price evolution over time, both in the long-run and in the short-run (with sudden peaks),

relative prices as captured by the developed price-based CFs are relatively similar regardless the timeframe considered.

Figure 4.5 : CFs based on 50 year-average prices as a function of CFs based on 10-year-average prices: correlation for 60 mineral resources, considering Cu as reference mineral resource



4.4.3 Strengths and weaknesses

Strengths and weaknesses of the price-based characterization method are discussed, both in absolute terms (considering this method only) and in relative terms (comparison with other, widely-used, impact assessment methods), regarding the following criteria: relevance to the question to be addressed; robustness of underlying assumptions; completeness (coverage of elementary flows); data quality (including uncertainty and representativeness); consistency with other impact categories; operationalization and communication.

4.4.3.1 Relevance

The TF mineral resources of the UNEP Life Cycle Initiative set the issue of "value" as of utmost importance regarding the safeguard subject for "mineral resources" (which is "the potential to make use of the value that mineral resources can hold for humans in the technosphere"; Berger et al., 2020). The price-based characterization method enables to capture "value" in the impact assessment step, especially to what concerns the functions that resources may have for humans in the technosphere. When combined with a method to account for dissipated resources at the LCI level, it enables to capture the loss of value of mineral resources as induced by a product-system over its life cycle, i.e. the damage to the safeguard subject as defined by the "task force mineral resources".

Methods to account for dissipation in particular encompass the JRC-LCI method as considered in the case study of this Chapter. Further combination of price-based CFs with other methods to account for

dissipative flows at the inventory level is additionally conceivable, e.g. with the method developed by Owsianiak et al. (2022) that enables to distinguish the actual dissipative emissions of resources to environment, from the non-dissipative ones, in the LCI step in mass units. Yet in the latter case, the associated robustness of conceptual foundations for the combination between such LCI-based methods and price-based CFs (e.g. regarding consistency in temporal perspectives) and associated potential issues of operationalization (e.g. nomenclatures of elementary flows) still require to be assessed.

It is noteworthy that more generally, price-based CFs may be directly combined with (i) classical approach to resource accounting in LCIs, which consists in reporting resources extraction from ground, or even (ii) in combination with LCIA methods that apply to current LCI (e.g. average dissipation rate, ADR, and lost potential service time, LPST, methods developed by Charpentier-Poncelet et al., 2021, 2022c; for estimating the impacts of dissipative flows of metals). These possible combinations shall be further explored regarding a number of aspects, including actual complementarity (e.g. in terms of conceptual ground for these methods, and operationalization) and consistency in terms of assumptions, defined problem and scope.

4.4.3.2 Robustness

This method builds on a limited number of both hypotheses and layers of data, whose uncertainty would add in the derivation of CFs. Still, it builds on one fundamental hypothesis: historical market prices of mineral resources are assumed to represent a best available proxy for their "values" in the technosphere and representative for resource prices in the near future. At this stage, there is not only no consensus on the way resource value shall be captured in LCIA of mineral resource use; there is also still no consensus on what the concept of "value" covers and how it should be defined. We consider that market prices of mineral resources represent the way that these resources are valued by economic actors, using them for the specific functions they provide. On the production side, market price is driven by a number of parameters. Energy consumption, in particular, represents a relevant component. Anyway, value of resources should reflect also their accessibility and the difficulties to get the resource available for their use in a product system (including the energy necessary for mining and refining). Therefore, we consider that costs for energy consumption should be considered in the impact assessment of resources. As future development of the method, the possibility to decouple the costs for energy from the resource value should be investigated.

It is also recommended to grant consistency between the inventoried dissipative flows and their corresponding CFs. This can be difficult in some cases, as for example dissipated metals in unrefined ores may have a value lower than that of refined metals. Still, we would recommend to use the price of refined metals as best proxy available (in the absence of more precise price figures). This is, however, a limitation needing further exploration.

Still, on the demand side, the price that is paid by economic actors is conditioned by the benefit that they will make from the use of these mineral resources. In terms of robustness of the underlying assumptions, it can be considered that the use of resources prices well fits as a proxy to determine their value as intended in this Chapter. The use of proxies has been adopted also by other impact assessment methods. For example ADP CFs are built considering that resource content of the continental crust (assuming 12 km depth) is a correct proxy for the ultimate reserve; which is further assumed to be a correct proxy for ultimately extractable reserve in the computation of CFs (van Oers et al., 2020a). Similarly, Owsianiak et al. (2022) assume that average concentration in the continental crust is a good proxy threshold for mineral resources accessibility, and that all chemical elements in

extracted mineral ores (even those in concentrations close to 0) are mineral resources. Therefore, we consider that (i) the price-based method developed in this Chapter enables to account for the loss of value of mineral resources, which makes it fully relevant as this topic is core according to the "task force mineral resources" recommendations, and (ii) there is some trade-off regarding robustness of the underlying assumptions (here considering “price” as a good proxy for “value”), yet acceptable in view of assumptions made in other classically implemented LCIA methods for mineral resource use.

4.4.3.3 Data quality and completeness of coverage

CFs are based on mineral resources market price data which overall can be qualified of good quality. This encompasses (i) reliability, (ii) representativeness and (iii) completeness:

i) Prices are by definition a quantified value agreed upon and communicated between stakeholders (sellers, buyers and potentially transparently available to market). In this study, data are drawn from the USGS. Therefore, both the nature of the data at stake and their source as used for CFs compilation make them reliable, in absolute terms (relatively low uncertainty) and in relative terms as compared to other types of data (in particular physical flows) classically implemented in LCA calculations;

ii) Representativeness here refers to both temporal and geographical representativeness. Data over a 50-year interval are implemented in the CFs, so that temporal representativeness may be considered good. Shorter temporal scopes moreover show rather limited influence on differences in CFs, as discussed in section 4.4.2. Moreover, geographical representativeness is also expected to be good, with many metal markets classically at a worldwide scale;

iii) Finally, coverage of substances is rather large. CFs have been developed for 66 minerals and chemical elements, which is e.g. comparable to the good coverage in ADR/LPST methods and in the updated ADP method (respectively 61 metals covered, and 76 chemical elements covered; Charpentier-Poncelet et al., 2022c; van Oers et al. 2020a). One asset of the price-based CFs relies in particular on the possibility to consider not only chemical elements but instead both chemical elements and minerals as “mineral resources”.

4.4.3.4 Consistency with other impact categories, operationalization and communication

The price-based method to account for resources value loss, as developed in this study with respect to mineral resources, may be further extended to other types of natural resources. This in particular includes fossil resources, while the applicability to other natural resources such as land or freshwater is still to be explored and may be questionable.

Price-based CFs as developed in this study are available in Appendix C. They are ready for use by practitioners, either directly combined with classical approach to account for mineral resources extracted from ground in LCI datasets, or with more recent method to account for dissipative flows, such as the JRC-LCI approach (as described in Chapter 3). Moreover, the concept of "value loss", that is captured by these CFs when combined with dissipative flows in LCI datasets, may be adequately understood by (and therefore communicated to) decision-makers or non-expert public audience. However, consistency with other impact categories requires careful evaluation, especially regarding timeframe and problem definition.

4.4.4 Improving CFs reliability and completeness: a way forward

Despite overall good quality (including representativeness) of the CFs as computed in this study, they may be further improved in the future in a number of ways.

Firstly, CFs for chemical elements refer to metals in their refined form; whereas losses in the life cycle are not necessarily in such metal form, but rather e.g. in oxidized form and therefore of lower value. Moreover, in one case, the price of a material (steel) was used as a proxy for the price of the major metal it is composed of (iron). The CFs as listed in this study accordingly tend to overestimate the impact of dissipative losses in the production steps along the life cycle of products and systems. Secondly, it is noteworthy that some commodities (e.g. rare earths) are primarily traded on over-the-counter markets (i.e. directly between two parties and without a central exchange or broker). This implies less transparent data, and as a consequence potentially more uncertain reporting in databases such as that of the USGS.

These limits may be overcome by exploring further data sources. These include e.g. data published by the London Metal Exchange (LME, 2022), Fastmarkets (Fastmarkets, 2022), Oanda (Oanda, 2022), etc. Exploring these other data sources is beyond the scope of this study, but may be relevant in further developments, as it will potentially open the door to:

- More complete data, i.e. potentially integrating additional mineral resources beyond those covered in Figure 4.1 and Figure 4.2, including disaggregation of the CF associated with rare earth elements (REEs) into CFs for individual REEs;
- Less uncertain data, including intervals of values to be integrated in sensitivity analysis;
- Evaluation of the relevance of regionalization of CFs, at a level of disaggregation (in terms of countries/regions) to be determined. “Relevance” could here be explored both in terms of (i) any actual, observable, difference in prices for each mineral resource (as a function of regions where these are sold); and (ii) conceptual validity of such potential regionalization (in a context where the developed impact assessment method intends to evaluate value loss for humans). This latter point would require exploring how far the LCIA method shall be approached either in one single global perspective (i.e. one single value of each mineral resource for humans, independently on any price difference by region), or shall instead account for potentially different (regional) valuations by humans, as might be reflected by different prices per region. One may however expect that regionalization is less relevant in the context of mineral resources than in case of other environmental and resource issues classically addressed in LCA (e.g. land and water resources).

Moreover, while mineral resource elements may hold a value for humans, in some cases, they may reduce the accessibility of other mineral resource elements, and/or the functionality of these other elements, therefore negatively affecting the value of these other resources. This is e.g. the case of arsenic in copper concentrates, which is deleterious for downstream resources recovery though smelting and refining processes. Each smelter sets diverse limits for contaminants, reflected by diverse penalties potentially escalating with increasing concentration (Salomon-de-Friedberg and Robinson, 2015). More generally, the content of impurities is sometimes used to reflect quality of recycling (Tonini et al., 2022). It is also considered that the presence of potential impurities is somehow factored in by the price paid by a smelter. However, these aspects are not addressed in the LCIA method presented in this article. Further developments both at the inventory level (within the JRC LCI method) and at the impact assessment level would be relevant to further reflect how far impurities affect the accessibility and value of other mineral resources in a material (whether a product or a waste).

Finally, it is noteworthy that CFs shall be updated in a sufficiently regular basis, at a frequency that depends on the temporal perspective considered for the CFs; that is, more frequent updates for CFs averaged over 10 years than regarding CFs averaged over 50 years. The use of a 50-year timeframe as a reference allows also to reduce the need of frequent updates due to the smoothing effect associated with such a long timeframe.

4.5 Conclusions and perspectives

This article presents a price-based characterization method to quantify the damage induced by mineral resource use in LCA and, in particular, the loss of value that abiotic resources (primary and secondary) may hold for humans in the technosphere (Schulze et al., 2020a). The price of a given resource is used as a representative proxy for the functions that such resource has in the economy. The CFs of this LCIA method are calculated for 66 minerals considering configurations (e.g. clays and gypsum) and chemical elements (e.g. copper and zinc) based on their 50-year price-average, considering copper as the reference mineral resource. Alternative CFs are moreover made available regarding other temporal perspectives (10, 15, 20 and 30 years). General considerations on the method are not affected by changes in the chosen reference substance (e.g. copper, gold or antimony). The temporal scope of the method is rather oriented to short-term assessment, and geographical scope is global. The potential use for longer timeframes and the relevance of regionalization should be further explored.

The 50-year-price-based CFs are tested in this article on one cradle-to-gate case study (copper production), in combination with the JRC-LCI method which accounts for dissipative mineral resource flows at the inventory level. This combined use of the JRC-LCI and the price-based CFs enables to capture the loss of value of mineral resources as induced by a product-system over its life cycle. The developed price-based CFs may alternatively be further combined with (i) other methods to account for resource dissipation in the LCI of products and systems, e.g. methods that consider only emissions of mineral resources to environment as dissipative flows; (ii) classical approach to accounting of resources extraction from ground; or (iii) some mineral resource LCIA methods that apply to current LCI datasets, yet without capturing the value of resources (e.g. ADR and LPST). Such combinations shall be further explored, in particular in terms of consistency (e.g. of underlying assumptions in each method) and operationalization.

The developed price-based characterization method is relevant to address the issue of mineral resources value loss in LCA. Associated CFs enable good coverage of elementary flows, with using as a basis underlying data of good quality. These CFs could be easily understood by LCA practitioners and non-expert public (including policy makers). They moreover offer relevant perspectives for coherently accounting for natural resources (including mineral resources) in LCA. Yet, despite this overall satisfying level of quality, the developed CFs offer in the meantime perspectives for short- and long-term improvements. In the short-term, these CFs may be further refined considering (i) higher disaggregation at the level of substances, including distinction between the form of metals (e.g. as metal at a high purity versus in oxidized form); (ii) extension to additional mineral resources, not covered yet; and (iii) potential regionalisation of CFs (e.g. at the level of some regions of the World; e.g. the EU). Finally, it is noteworthy that the developed CFs have so far not been tested extensively to a broad number of case studies. Therefore, potential users of these CFs should be aware of this limitation. It is recommended that these CFs should be further tested before they are applied routinely in LCA studies. The following Chapter 5 offers a further elaboration on the impact pathway developed in this Chapter 4, and associated tests on case studies.

5 Chapter 5 – Application of the JRC-LCI and JRC-LCIA methods to multiple case studies, including discussion on possible refinement

This Chapter is essentially drawn from:

Lai, F., Beylot, A., 2023. Loss of mineral resource value in LCA: application of the JRC-LCI method to multiple case studies combined with inaccessibility and value-based impact assessment. The International Journal of Life Cycle Assessment 28, 38–52. https://doi.org/10.1007/s11367-022-02110-4

Contribution of the co-authors:

- Frédéric Lai: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.
- Antoine Beylot: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

5.1 Introduction

The JRC-LCI method is presented in Chapter 3 (Beylot et al., 2021). It builds on the definition of resource dissipation as provided in Chapter 2 (Beylot et al., 2020b). It consists in reporting dissipative flows of mineral resources at the unit process level, in mass units (Beylot et al., 2020a; 2021). The JRC-LCI method captures, in the LCI step, the flows that are known to be dissipative, or still will be in a short-term perspective. Such short-term perspective for mineral resources appears particularly adapted to support sound policy-decision making, compared to any consideration in the very far future which is generally of lower importance in policy contexts. The JRC-LCI method moreover enables to discriminate the most contributing steps in the life cycle, and to trace the most contributing flows at each of these steps, which is key to support more resource-efficient solutions in an eco-design approach.

This method however requires important amendments to existing LCI datasets in terms of explicitly tracing dissipative flows in datasets, whereas these flows are not addressed as such in current practices of LCI compilation in standard LCI databases. In this respect, at the current stage of development, the JRC-LCI method still faces an issue of operationalization. It was successfully applied to two case studies, thus showing a first proof of applicability that calls for additional case studies to confirm the developed insights (Beylot et al., 2020a; 2021). In particular, Beylot et al. (2021; see Chapter 3) considered a cradle-to-gate copper production case study, with focus on direct dissipative flows only and excluding any dissipation issue at the use and end-of-life phases of products (e.g., through landfilling). Moreover, consideration of indirect emissions in the background system, in addition to direct dissipative flows in the foreground system, is necessary to actually support comprehensive life-cycle calculations. Consideration of the background system in LCA of products however requires that secondary datasets (e.g., from the ecoinvent database) are populated with dissipative flows. This shall be further addressed step by step, firstly by extending the number of application to datasets (i.e., additional case studies) and elaborating on how to further extend to a larger number of datasets, up to whole LCI databases.

The JRC-LCI method, by definition implemented at the inventory level, may be further combined with LCIA approaches. Price-based CFs are suggested to be applied to dissipative flows, using market price data of mineral resources to capture value loss in the impact assessment (Chapter 4; Ardente et al., 2023).

In this context, this Chapter aims at further testing the JRC-LCI method at the inventory level, by applying it to 10 cradle-to-gate case studies (primary production of raw materials) as well as one case study considering the full life cycle of a mineral raw material–based product (lithium-ion battery for electric vehicles). More specifically, the objectives of this Chapter are threefold:

(i) further demonstrate the applicability of the JRC-LCI method beyond the proof of concept as published so far;
(ii) pave the way towards the upscaling of this approach, in whole LCI databases, towards routine consideration of resource dissipation in LCA; and
(iii) propose a new LCIA approach, building on the EC-JRC price-based model, so as to better capture the impacts relative to the potential dissipation of mineral resources, in particular with capturing the duration of inaccessibility.

5.2 Method

5.2.1 Adjustment to the JRC-LCI method to account for potentially dissipative flows

In this study, a slight amendment of the JRC-LCI method, in which a given time perspective shall be pre-defined (Beylot et al., 2021; Chapter 3), is proposed: no specific temporal perspective is defined for reporting "potentially dissipative" resource flows in the LCI step. Instead, it is suggested that

(i) the temporal perspective is accounted for at the LCIA stage (through the integration of resource inaccessibility durations in CFs; see section 5.2.2);
(ii) the same dissipation compartments as those initially considered by the EC-JRC are kept.

The term "potential", as already introduced by Owsianiak et al. (2022) regarding dissipative emissions in LCA, is also used here: we suggest that a resource flow is no longer classified dissipative per se (as originally suggested by Beylot et al., 2021; Chapter 3) but rather "potentially dissipative".

This amendment of the approach does not change its implementation at the LCI stage; i.e., the JRC-LCI method shall be implemented in two steps: firstly, mapping the flows of mineral resources into and out of the unit processes under study ("resource flow analysis" – RFA); and secondly, identifying potentially dissipative flows and reporting them in the LCI at the unit process level (Beylot et al. 2020a; 2021). It is noteworthy that among the output flows of substances, only the ones originating from mineral resources can be classified potentially dissipative. In this study, mineral resource flows are identified following the set of rules as suggested in Chapter 3 (Beylot et al., 2021), aligned with those considered in ecoinvent:

- The mineral or aggregate (e.g., gypsum, sand) is to be considered the resource if it holds a value as such.
- "If the value of a mineral ore is to host elements only" (Beylot et al., 2021), the target elements within the ore are considered the resources.
- Any chemical element, mineral, or aggregate providing a significant function within products-in-use in the technosphere are also to be considered resources.

The nomenclature for mineral resource flows is based on the list of minerals classified as "resources from ground" in the EF reference package (version 3.0; EC, 2019).

5.2.2 Proposal for a life cycle impact assessment approach

5.2.2.1 Impact pathway

Over their life cycle, product systems require inputs of mineral resources either directly originating from the ecosphere or from the technosphere as a result of successive transformations. While a part of these resources remains in the technosphere, providing a utility to humans, another part ends up in stocks. This compromises the accessibility to these resources for humans over a certain time span, which is dependent on the stock. As a consequence of this inaccessibility, the resources are rendered unable to provide any utility to humans. As long as these mineral resources are inaccessible, humans cannot make use of the value "that [they] can hold […] in the technosphere" (here recalling the terms used by Berger et al., 2020, to define the safeguard subject for "mineral resources").

In this context, the proposed LCIA approach aims at addressing the following question:

How to quantify the loss of value associated with the inaccessibility of mineral resources induced by a product system over its life cycle?

As a response to this question, the following impact pathway is defined (Figure 5.1):

i) A product system uses primary and secondary mineral resources. At the inventory level, flows of mineral resources (in mass units) are reported as respectively entering/exiting the system from/to the ecosphere and technosphere. Among the output flows of resources, a part is classified "potentially dissipative".

ii) This partly renders resources inaccessible to future users, for a more or less long time span (midpoint level in the impact pathway). The extent of this inaccessibility may be expressed as a duration over which the resources are inaccessible to future users, in years. This duration may vary as a function of the dissipation compartment (e.g., in ecosphere versus in landfills) and as a function of the resources (e.g., base metals in landfills may be assumed more accessible than rare metals because of potentially larger concentrations). The consideration of the duration of inaccessibility in this impact pathway, also called "residence time" by other authors (Zimmermann and Gößling-Reisemann, 2013), enables accounting for the severity of dissipation, in a context where "long residence times […] [increase] the severity of dissipation" (Zimmermann and Gößling-Reisemann, 2013).

iii) This inaccessibility results in the loss of the value these resources hold for users; that is, it damages the safeguard subject for "mineral resources" within the AoP "Natural Resources" (endpoint level). This value may be reflected through the resource price, as suggested by the EC-JRC (Chapter 4; Ardente et al., 2023).

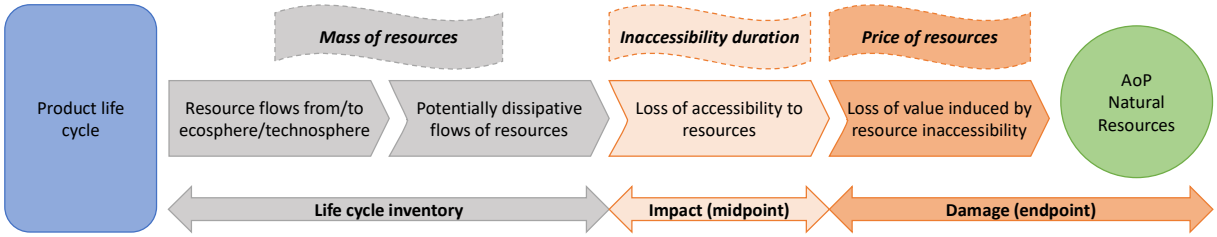


Figure 5.1: Impact pathway relative to the use of mineral resources over the life cycle of a product system

Given the level of details of resource inaccessibility data (which are rough and not resource-specific data; see section 5.2.2.2) considered in this study, it is decided, in the following, solely to focus on the endpoint approach (i.e., on the damage to the safeguard subject for "mineral resources") that combines the midpoint considerations (i.e., resource inaccessibility) with detailed price data.

5.2.2.2 Characterization approach and factors at endpoint level

This endpoint approach builds on the price-based LCIA approach suggested by the EC-JRC (Chapter 4; Ardente et al., 2023). However, while the latter solely includes an economic dimension, the approach here proposed additionally integrates a temporal dimension (expressed as a duration of resource inaccessibility). The calculated damage accordingly captures not only the value of the resource but also the temporal horizon over which this value is lost.

Data regarding durations of resource inaccessibility are directly drawn from Dewulf et al. (2021) who

(i) identified human compromising actions (e.g., landfilling) leading to inaccessibility of resources in various stocks (e.g., landfills);
(ii) identified factors (e.g., technological or societal) affecting the duration of inaccessibility;
(iii) estimated durations to measure the degree of inaccessibility of raw materials depending on the stock they are embedded in. As a result, rough estimates of inaccessibility duration were provided by the authors for each stock, common to all raw materials in a given stock, with distinguishing one "best estimate" value and time spans (Table 5.1).

Table 5.1: Inaccessibility durations of raw materials in several stocks/compartments of dissipation, as estimated by Dewulf et al. (2021)

Stocks as considered by Dewulf et al. (2021)	**Dissipation compartments as considered in the JRC-LCI method (Beylot et al., 2020a; 2021)**	**Inaccessibility duration *(best estimate)***	**Inaccessibility duration *(lower bound of the time span)***	**Inaccessibility duration *(upper bound of the time span)***
Tailings	Final waste disposal facilities	65 years	25 years	500 years
Landfills		65 years	25 years	500 years
Dispersed stock in the technosphere *(downcycling)*	Products-in-use in the technosphere *(low-functional recycling)*	500 years	500 years	Infinite
Dispersed stock in the environment	Environment	500 years	500 years	Infinite

In a first approach, the endpoint CFs are based on: i) the best estimates regarding the duration of resource inaccessibility in each compartment (Table 5.1); and ii) price data averaged over 50 years, with considering antimony (Sb) as reference for the calculations, drawn from Chapter 4 (Ardente et al., 2023). These CFs and damage (value loss) resulting from the dissipation of mineral resources are calculated according to the following equations:

Equation 3: $$CF_{i,j} = \frac{Price_{Av,i}}{Price_{Av,Sb}} . ID_j$$

Equation 4: $$Value\ loss\ (VL) = \sum_{\substack{1 \le i \le n \\ 1 \le j \le 3}} m_{ij} \ . \ CF_{i,j}$$

Where:

- $CF_{i,j}$ = characterization factor associated with resource i and dissipation compartment j, with Sb as reference substance [$years_{Sb\ €eq}$];
- $Price_{Av,i}$ = price of resource i averaged over 50 years [€/kg];
- $Price_{Av,Sb}$ = price of Sb as reference substance, averaged over 50 years [€/kg];
- ID_j = inaccessibility duration relative to the dissipation compartment j [years];

- m_{ij} = mass of resource i in dissipation compartment j [kg], as generated over the life cycle of the product system under study;
- VL = value loss resulting from the dissipation of mineral resources [$kg.years_{Sb\ €eq}$], as induced by the product system over its life cycle.

The full list of CFs is provided in Appendix D. VL is expressed as a mass of mineral resources over a certain duration integrating the value of these resources in perspective to (i.e., divided by or "normalized" over) the value of Sb as the reference resource (as indicated by the subscript Sb €eq). In this sense, VL reflects the severity of resource deprivation to the society: the larger the duration of inaccessibility, mass, and value of resources, the higher the severity of value lost to other users.

5.2.3 Case studies description

5.2.3.1 Product systems and associated ecoinvent inventories

This study intends to demonstrate further the applicability and relevance of the JRC-LCI method to account for issues relative to the use of mineral resources, beyond its proof of concept. In particular, the application of the JRC-LCI method to multiple case studies aims at exemplifying its potentialities to support the development of more resource-efficient solutions by (i) quantifying the total amount of mineral resources potentially dissipated along different product systems and (ii) identifying the main hotspots (in terms of life cycle phases, compartments, or type of resources) driving the dissipation of mineral resources. In this context, 11 case studies are considered with distinguishing two main types of product systems:

- "Cradle-to-gate" systems, considering the primary production of respectively 9 metals and 1 non-metallic mineral raw material: aluminum (Al), cobalt (Co), copper (Cu), lithium (Li), manganese (Mn), nickel (Ni), platinum group metals (PGMs), rare earths (RE), silicon metal (Si), and graphite. The functional unit for these product systems is defined as "the primary production of the mineral raw material, considering one kg of the target element within the output material". The system boundaries encompass all unit operations from the ore extraction from ground (mining) and its concentration to refining (metallurgy).

- A "cradle-to-grave" system, considering the life cycle of a lithium-ion (lithium manganese oxide - LMO) battery (LiB) for electric vehicles. In this case, the reference flow is defined as "one LMO battery for electric vehicles", which corresponds to the functional unit "providing a nominal capacity of 2.1 kWh over a service life of 100,000 km". This study particularly focuses on the mineral raw materials (respectively the active materials and collector foils) composing the two main components of the battery cell: lithium manganese oxide ($LiMn_2O_4$) and Al in the cathode; graphite and Cu in the anode. Regarding these raw materials, a whole life cycle perspective is considered (i.e., accounting for dissipation along their production chain). The system boundaries additionally include (i) the battery manufacture encompassing the cathode, anode, and battery cells, as well as the battery assembly; (ii) the use phase in the electric vehicle; and (iii) the end-of-life (EoL) disposal including the potential functional recycling and landfilling.

Data relative to these different product systems are drawn from the ecoinvent database, in its 3.7 version, considering the "undefined" (i.e., unlinked and unallocated) unit processes as found in ecoQuery (see Table 5.2 and Appendix D; ecoinvent, 2021).

Table 5.2: Ecoinvent inventories associated with the LiB system, including the cradle-to-gate production of its raw materials

Product system	Ecoinvent unit process (v3.7)	Operations covered in the unit process
Al	Bauxite mine operation	• Mining (including blasting) • Beneficiation (e.g. including washing, screening or drying)
	Aluminium hydroxide production	• Extraction of $Al(OH)_3$ (grinding, digestion and precipitation)
	Aluminium oxide production	• Calcination of $Al(OH)_3$ into Al_2O_3
	Aluminium production, primary, liquid, prebake	• Aluminium smelting
	Aluminium production, primary, ingot	• Batching, metal treatment and casting
Cu	Copper mine operation and beneficiation, sulfide ore	• Mining (including blasting) • Beneficiation
	Smelting of copper concentrate, sulfide ore	• Smelting of Cu concentrate
	Electrorefining of copper, anode	• Electrorefining of Cu anode
Li	Spodumene production	• Mining (including blasting)
	Leaching of spodumene with sulfuric acid	• Sulfuric acid digestion of spodumene
	Lithium brine inspissation	• Inspissation of Li brine
	Lithium carbonate production, from concentrated brine	• Production of Li carbonate (e.g. including purification, carbonation)
Mn	Manganese concentrate production	• Mining (including blasting) • Beneficiation (e.g. including crushing, grinding, classification)
	Manganese (III) oxide production	• Roasting of Mn concentrate
Graphite	Graphite production, battery grade	• Mining (including blasting) • Beneficiation (e.g. including flotation) • Drying, sieving, conditioning
LiB	*(Raw materials production)*	*(cf. graphite, Cu, Mn, Li and Al)*
	Lithium manganese oxide production	• Roasting of Mn oxide and Li carbonate
	Cathode production, $LiMn_2O_4$, for lithium-ion battery	• Cathode production
	Anode production, graphite, for lithium-ion battery	• Anode production
	Battery cell production, Li-ion	• Production of single cells for Li-ion battery
	Battery production, Li-ion, rechargeable, prismatic	• Production of a battery pack for Li-ion battery
	Transport, passenger car, electric	• Operation of an electric passenger car

It is noteworthy that the JRC-LCI method has already been applied to the case of Cu cradle-to-gate production, building on ecoinvent v3.5 (Chapter 3; Beylot et al., 2021). Regarding this case, the present study therefore consists in updating the accounting for dissipative flows considering updated datasets relative to the copper sector as now available in ecoinvent v3.7 (Moreno Ruiz et al., 2020).

It is also noteworthy that the application of the JRC-LCI method is limited to the foreground of each product system in this study. This implies that only direct dissipation of mineral resources is accounted for, while indirect dissipation (i.e., relative to the background system) is disregarded. The accounting for these indirect dissipative flows would require that they are accounted for in the whole LCI database, which is not the case so far. Moreover, in the following, the impact assessment exclusively focuses on the LiB case study, which includes some of the cradle-to-gate mineral and metal production systems as also individually investigated (namely Al, Cu, Li, Mn, and graphite).

5.2.3.2 Data and scenarios

The implementation of the JRC-LCI method to the ecoinvent-based case studies is described in specific terms (in Appendix D) with focus on the case of Ni cradle-to-gate production. On another note, in the absence of specific information from the ecoinvent database, the LiB EoL disposal is modeled considering several assumptions relative to the LiB recycling rate based on literature data. Moreover, the non-recycled part of the LiB is assumed to be disposed of in landfills. In this study, the LiB EoL disposal is declined into three different scenarios reflecting the following:

- The current performance in LiBs recycling (in the following, referred to as "current EoL disposal" scenario). A 5% recycling rate (RR) is considered in this scenario, corresponding to the LiB RR in the European Union in 2019 (Sommerville et al., 2020).
- A "conservative future EoL disposal" scenario. A 40% RR is assumed in this case, based on Ziemann et al. (2018) who assumed that such a rate might realistically be achievable in the medium term for Li recycling from LiBs.
- An "optimistic future EoL disposal" scenario. An 80% RR is assumed in this case, similarly based on the assumption set by Ziemann et al. (2018).

In practice, the efficiency of metal recovery from LiB recycling may vary depending on the metal considered, as some metals are better recovered than others (Sommerville et al, 2020). Yet, in the absence of detailed recycling data specific to the LMO battery (to our knowledge), it is here assumed that the different RRs set in this study apply to the battery as a whole (i.e., to each raw material composing the battery).

5.3 Results and discussion

5.3.1 Dissipation of mineral resources at the inventory level

The JRC-LCI method enables the identification of potentially dissipative resource flows at the inventory level, in mass terms, induced all along production chains (cradle-to-gate perspective; see section 5.3.3.1 and Appendix D) or life cycles (cradle-to-grave perspective; see section 5.3.1.2). As a result, the total mass of direct potentially dissipative flows of mineral resources is quantified and associated hotspots (in terms of process steps, compartments or type of resources) responsible for resource losses are investigated for each case study. This analysis at the LCI level in this section 5.3.1, in mass terms, supports new insights on how the JRC-LCI method may be applied and support sound decision-

making on resource issues. Yet, this focus on flows at the LCI level does not provide information on impacts, by definition. In section 5.3.2, it is therefore complemented by a further analysis of the damage induced by these potentially dissipative resource flows, considering the severity of dissipation and the value of resources.

5.3.1.1 Potentially dissipative flows in the cradle-to-gate production of 10 raw materials

Along the production chains of the 10 mineral raw materials under study, the total mass of direct potentially dissipative mineral resource flows at the inventory level overall varies from 0.05 (graphite) to 994 kg/kg (PGMs; Table 5.3). In particular, this total mass is inferior to 0.94 kg/kg for five raw materials (graphite, Si, Al, Mn, and Ni), while it ranges from 2.4 to 7 kg/kg regarding four other raw materials (RE, Cu, Li, and Co). Finally, the case of PGM production significantly stands out from the other raw materials with several orders of magnitude of difference in mass terms (which is hereafter detailed).

Table 5.3 : Direct potential mineral resources dissipation in mass at the inventory level considering the cradle-to-gate production of 10 mineral raw materials

Mineral raw material (targeted resource)	Output product	Total mass of potentially dissipated mineral resources	Unit*	Losses of the targeted resource (in % of the total mass of potentially dissipated resources)
Al	Al ingot	0.46	kg/kg Al in Al ingot	37%
Co	Refined Co	7.0	kg/kg Co in refined Co	0%
Cu	Cu cathode	2.4	kg/kg Cu in Cu cathode	18%
Li	Li_2CO_3	3.3	kg/kg Li in Li_2CO_3	10%
Mn	Mn_2O_3	0.58	kg/kg Mn in Mn_2O_3	88%
Ni	Ni class 1	0.94	kg/kg Ni in Ni class 1	26%
PGMs	Refined PGMs	994	kg/kg PGMs in refined PGMs	0%
RE	RE oxides	2.4	kg/kg RE in RE oxides	24%
Si	Si metal	0.43	kg/kg Si in Si metal	72%
Graphite	Graphite battery grade	0.05	kg/kg graphite in graphite battery grade	99%

* The unit is here expressed as the total mass (in kg) of potentially dissipated mineral resources per kg of the targeted resource contained within the output product (e.g. 1 kg of Li in Li_2CO_3).

From a process perspective, metallurgical processes are responsible for the largest share of the potentially dissipated resources in the process chain of five raw materials (Figure 5.2): Ni, RE, Si, Li, and Al (from 56% up to 99% of the total mass). Conversely, mining processes account for the largest share

of the potentially dissipated resources with respect to Mn (83% of the total mass), Cu (61%), and especially PGM (nearly 100%) productions.

In terms of compartments, final waste disposal facilities stand out as the main dissipation compartment in nine cradle-to-gate systems, encompassing from 87% (Si metal production) to 100% (Mn and graphite productions) of the potentially dissipated resources (Figure 5.2). Regarding the case of PGM production, final waste disposal facilities however only account for 16% of the total mass, with the remaining 84% potentially dissipated to the environment. As for the other raw materials, potential dissipation to the environment covers 13% of the total mass in the case of Si metal production, while it shows very limited contributions with respect to the eight other raw materials (less than 7%). Finally, resource dissipation in products-in-use due to low-functional recovery (e.g., slags incorporated in cement production) was only encountered in four product systems (Cu, Co, Ni, and RE), although accounting for a very limited share of the total mass (less than 1%).

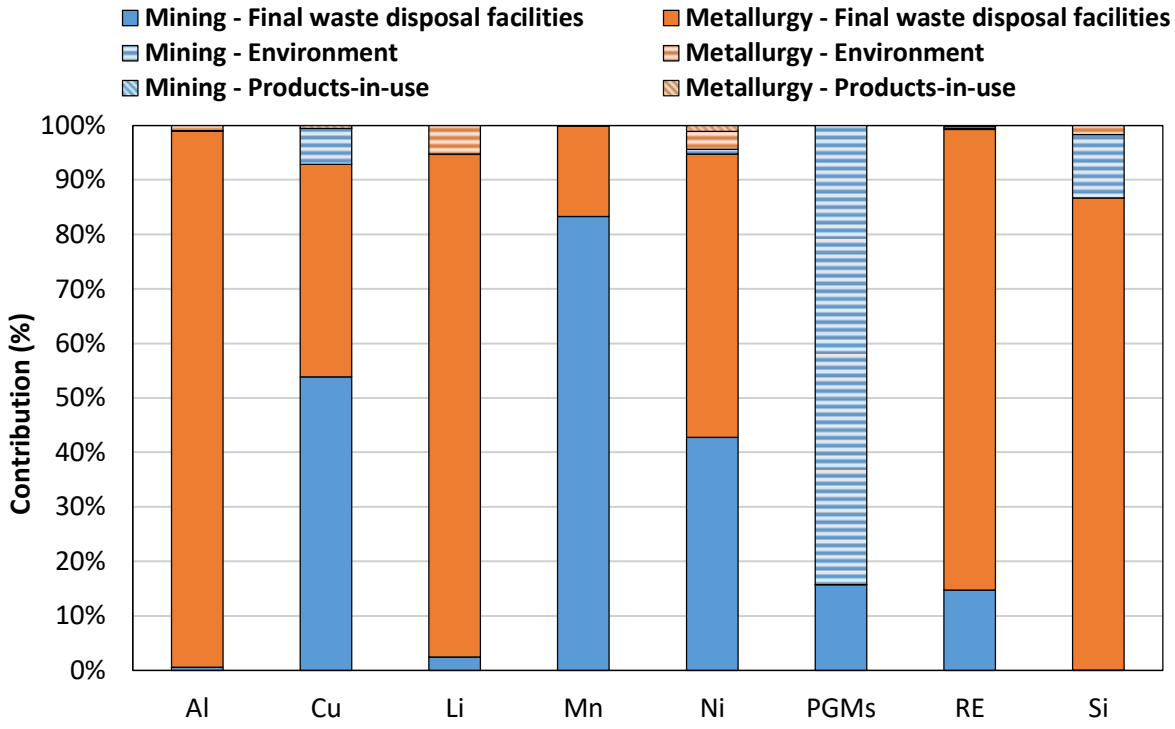


Figure 5.2: Direct potential mineral resources dissipation at the inventory level considering the cradle-to-gate production of 8 raw materials, with contributions per main process steps and dissipation compartments. Co and graphite are here excluded, given their aggregated ecoinvent datasets. Potentially dissipative flows induced by the production of each material include both the targeted resource (e.g. Cu potentially dissipative in the production of Cu cathodes), and other mineral resources (see also Table 5.3).

The potential dissipation of resources is primarily driven by process losses of the targeted resource (e.g., Si in the case of Si metal production) in the productions of Si, Mn, and graphite (from 72 to 99% of the total mass, which is inferior to 0.58 kg/kg; Table 5.3). With regard to PGM, Li, and Al productions, the potential dissipation of resources is primarily driven by the dissipative use of metals in particular embodied in ancillary inputs. Considering the PGM case, the Al and calcium embedded in explosives, and eventually emitted to the environment, respectively account for 41% and 32% of the total mass of potentially dissipated resources. Finally, non-metallic mineral resources also used as ancillary inputs

(e.g., sulfur or chlorine) represent the first contribution to resource dissipation in the productions of Cu, RE, Ni, and Co (from 54 to 89% of the total mass). It is noteworthy that losses of the targeted resource stand out in cases where the total mass of potentially dissipative flows is relatively limited (Si, Mn, graphite). Conversely, the dissipative use of metals and non-metallic resources stand out in cases where the total mass is relatively important (PGMs, Co, Li). This suggests that the mass of potentially dissipated resources may be primarily driven by the amount of ancillary inputs necessary to the raw materials' production processes. The larger the amount of ancillary inputs potentially dissipated is, the lower is the contribution (in %) of targeted resources to the total potential dissipation along the raw material production chain.

5.3.1.2 Potentially dissipative flows in the LiB life cycle

Over its life cycle, the LiB induces 613 kg of direct potentially dissipative mineral resource flows at the inventory level in the current EoL disposal scenario (Figure 5.3). In comparison, the conservative and optimistic future EoL disposal scenarios respectively result in 15% and 33% lower total mass of potentially dissipated resources. It is noteworthy that the mass of potentially dissipative flows provided for each scenario integrates all life cycle stages from raw materials' production to EoL disposal; accordingly, the results as mentioned in this paragraph are not proportional from one scenario to another, due to dissipative flows in steps earlier than EoL.

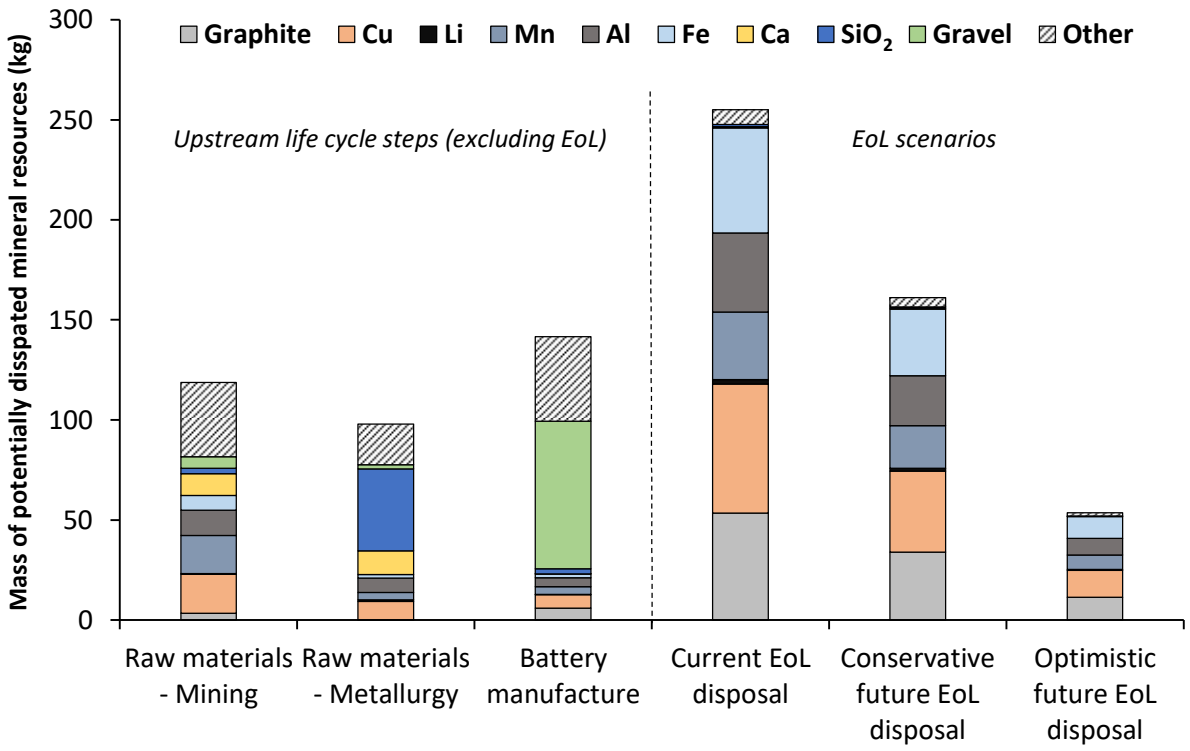


Figure 5.3 : Direct potential mineral resources dissipation in mass at the inventory level considering the life cycle of a LiB for electric vehicles, with contributions per mineral resources and life cycle stages. NB: the legend associated with each mineral resource (e.g., Cu) relates to the amount of this resource potentially dissipated at each stage of the battery life cycle

These discrepancies are driven by the EoL phase, in line with the different RRs defined in each scenario. In particular, EoL disposal stands for the largest contribution to resource dissipation in the current and

conservative future scenarios, accounting for respectively 42% and 31% of the total mass of potentially dissipative flows. Conversely, in the optimistic future scenario, EoL disposal only shows the lowest contribution to resource dissipation among all life cycle steps (13% of the total mass). The upstream steps associated with the raw materials' production and battery manufacture are moreover responsible for a significant mass of potentially dissipated resources, amounting to 358 kg of which 40% are due to battery manufacture, 33% due to mining, and 27% due to metallurgy. It is noteworthy that the LiB use phase does not induce any direct dissipation given that it does not require nor generate any direct input or output of mineral resources. Moreover, in terms of compartments, final waste disposal facilities stand out by far as the main dissipation compartment, as it accounts for more than 97% of the total mass of potentially dissipative flows in all EoL disposal scenarios.

Finally, from a resource standpoint, the potential dissipation in the EoL phase directly depends on (i) the mass of raw materials embodied in the LiB, and (ii) the RR, common to all raw materials in the LiB but specific to each scenario. As a consequence, the potential dissipation in the EoL disposal phase is primarily driven by the five resources the LiB is primarily made of: Cu, graphite, Fe, Al, and Mn (Figure 5.3). Moreover, regarding the upstream life cycle phases, the potential dissipation of resources appears to be primarily driven by (i) losses of Cu and Mn in tailings in their respective mining processes; (ii) the dissipative use of silica sand (SiO_2) as additive in Cu refining; and (iii) the gravel mobilized in the infrastructure relative to the battery manufacture.

5.3.2 Value loss induced by the potential dissipation of resources in the LiB life cycle

5.3.2.1 Contributions analysis

In a life cycle perspective, the LiB induces 9 647 kg.years$_{Sb\ €eq}$ of value loss when considering the current EoL disposal scenario. This shall be interpreted as follows: along the whole LiB life cycle, the total mass of resources rendered inaccessible is equivalent, in economic terms, to 9 647 kg.years of Sb. The value loss induced by the LiB life cycle respectively amounts to 7 469 and 4 979 kg.years$_{Sb\ €eq}$ in the conservative and optimistic future EoL disposal scenarios (respectively 23% and 48% less than in the first scenario; Figure 5.4).

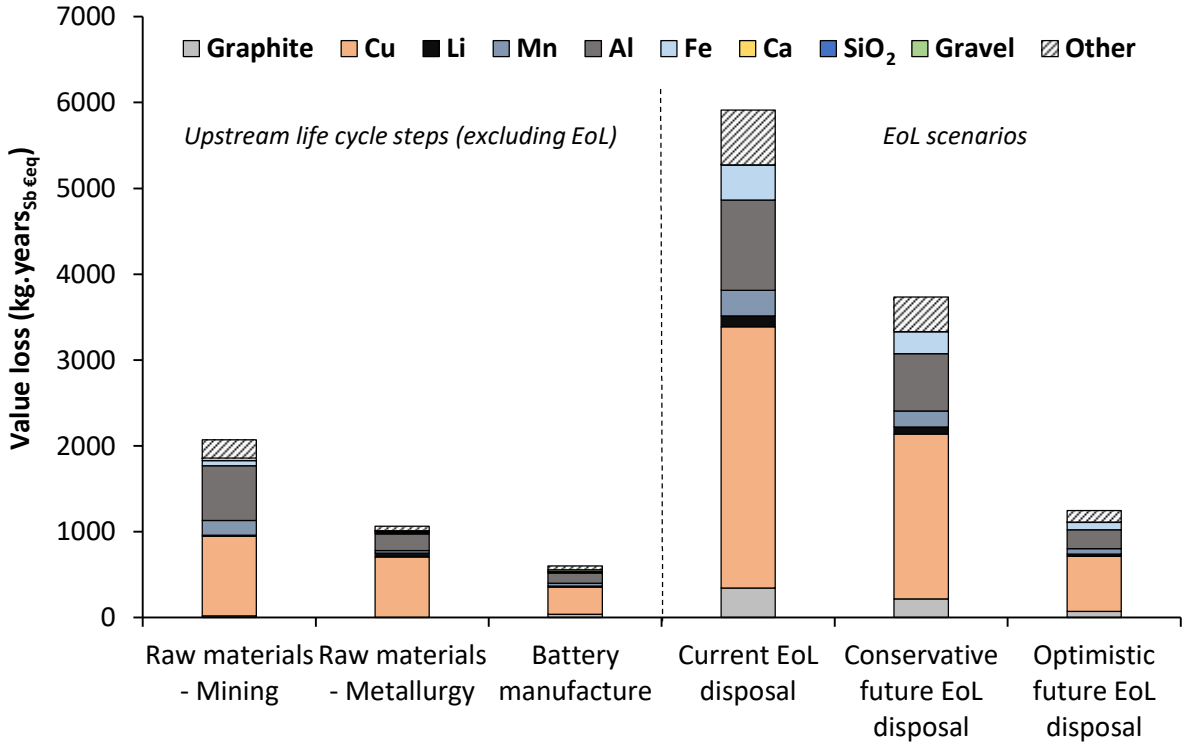


Figure 5.4: Value loss induced by the dissipation of mineral resources—contributions per resources and life cycle steps, considering the life cycle of a LiB for electric vehicles

Similarly to its contribution in mass, the EoL disposal phase accounts for the largest share of the total value loss in the current and conservative future scenarios, with respectively 61% and 50% of the total damage. The EoL disposal also stands for the second largest contribution in the optimistic future scenario, accounting for 25% of the total damage. Regarding the upstream life cycle steps, mining represents the second contribution to the total value loss in the current and conservative future EoL disposal scenarios (respectively 21% and 28% of the total damage), and the largest contribution in the optimistic future scenario (42% of the total damage). Finally, the contributions to value loss resulting from the metallurgy and battery manufacture steps are relatively limited (inducing respectively two and three times less damage than the mining step). This contrasts with their contributions in mass terms at the inventory level, in particular due to discrepancies in the value of the resources respectively lost in the mining step and in the metallurgy and battery manufacture steps as further explored hereafter.

In terms of compartments, final waste disposal facilities account by far for the largest share of the total value loss (85% up to 92% in all scenarios), in line with their largest contribution in mass terms (see section 5.3.1.2). This is despite their associated shorter inaccessibility duration as compared to the environment compartment (5 to 9% of the total damage, mostly driven by Al emissions during blasting operations) and products-in-use (3 to 6%, essentially driven by low-functional recycling of the Cu embodied in sludges produced during Cu anode production and subsequently recycled in clinker).

In terms of resource hotspots, the value loss induced by the LiB appears to be primarily driven by Cu whose contribution amounts to 52% in each scenario and more than 45% in each life cycle step. This large contribution is in particular driven by the large mass of Cu dissipated over the LiB life cycle combined with relatively important CFs. Moreover, Al also stands out as a hotspot with 21 to 24% of the total damage in all scenarios, whereas other mineral resources only show very limited

contributions (less than 6%). It is noteworthy that, while metallic as well as non-metallic resources (e.g., SiO_2, gravel) may stand out at the inventory level, only metallic resources stand out at the LCIA level. This discrepancy between LCI and damage is mainly driven by relatively large differences in CFs between metals (e.g., 364 $years_{Sb\ €eq}$ for the CF associated with Cu emitted to the environment) and minerals (e.g., 0.51 $years_{Sb\ €eq}$ for the CF associated with gravel emitted to the environment; see Appendix D). As a consequence, life cycle steps whose contributions at the inventory level are primarily driven by minerals (metallurgy and battery manufacture) show more limited contributions at the LCIA level.

Overall, such results offer different insights in comparison with other studies assessing the impacts of mineral resources use over the LiB life cycle. Indeed, while this study highlights that the EoL as well as upstream production phases may be responsible for such impacts, other studies, considering in particular depletion approaches, essentially identify the battery production phase (including the production of its raw materials) as hotspot with regard to mineral resource impacts, with almost no impacts for the EoL phase (excepting credits associated with recycling; Cusenza et al., 2019; Quan et al., 2022; Deng et al., 2017). This suggests that focusing on dissipated rather than extracted resources enables the identification of hotspots (in terms of life cycle steps) responsible for resource impacts that may arise all along the life cycle, which may ultimately be considered key to support more resource-efficient designs.

5.3.2.2 Sensitivity analysis: duration of resource inaccessibility

As acknowledged by Dewulf et al. (2021), the inaccessibility duration values are accompanied with a significant uncertainty which can be translated into very broad time spans, e.g., from 500 years up to infinite regarding the inaccessibility of resources emitted to the environment (Table 5.1Figure 5.1). As a first approach to assess the extent to which this uncertainty affects the LCIA results (considering the LiB case in the current EoL disposal scenario), five hypothetical scenarios and one reference scenario (Table 5.4) are further defined based on different resource inaccessibility durations set from the time spans provided by Dewulf et al. (2021; Table 5.1):

- Three scenarios differentiating a shorter or longer inaccessibility for some resources embedded in tailings and landfills (as sub-compartments of the "final waste disposal facilities" compartment): (i) an optimistic scenario of tailings reprocessing for metal recovery and landfill mining, with recovery of Cu, Fe, and Al from tailings/landfills after 25 years (waste scenario 1); and (ii) conservative scenarios regarding tailings/landfill mining, with durations of inaccessibility respectively set to 100 (waste scenario 2) and 500 years (waste scenario 3) for Cu, Al, Fe, Li, Mn, and graphite in tailings/landfills. In these three scenarios, the inaccessibility duration of other resources in final waste disposal facilities is kept identical to that of the reference scenario (65 years). Similarly, no changes are implemented with respect to resources emitted to the environment and in products-in-use (500 years).
- Two scenarios considering a longer inaccessibility for all resources emitted to the environment, respectively assuming 5 000 (emissions scenario 1) and 60,000 years (emissions scenario 2) of inaccessibility. In these scenarios, the inaccessibility duration of resources in final waste disposal facilities and products-in-use remains similar to that of the reference scenario (respectively 65 and 500 years).

Table 5.4 : Scenarios of resource inaccessibility, with distinguishing durations of inaccessibility as functions of resources and (sub-)compartments

<table>
<tr><th></th><th>Final waste disposal facilities</th><th>Environment</th><th>Products-in-use</th></tr>
<tr><td>Reference scenario</td><td>All resources
65 years inaccessibility</td><td rowspan="4">All resources
500 years inaccessibility</td><td rowspan="6">All resources
500 years inaccessibility</td></tr>
<tr><td>Waste scenario 1</td><td>Cu, Al and Fe in tailings/landfills
25 years inaccessibility
Other resources in final waste disposal facilities*
65 years inaccessibility</td></tr>
<tr><td>Waste scenario 2</td><td>Cu, Al, Fe, Li, Mn and graphite in tailings/landfills
100 years inaccessibility
Other resources in final waste disposal facilities
65 years inaccessibility</td></tr>
<tr><td>Waste scenario 3</td><td>Cu, Al, Fe, Li, Mn and graphite in tailings/landfills
500 years inaccessibility
Other resources in final waste disposal facilities
65 years inaccessibility</td></tr>
<tr><td>Emissions scenario 1</td><td rowspan="2">All resources
65 years inaccessibility</td><td>All resources
5 000 years inaccessibility</td></tr>
<tr><td>Emissions scenario 2</td><td>All resources
60,000 years inaccessibility</td></tr>
</table>

* Final waste disposal facilities include the disposal of tailings/landfills as well as of infrastructure waste (whose disposal is not defined in the ecoinvent datasets).

It is to be noted that this analysis solely focuses on the sensitivity of LCIA results to inaccessibility durations, without considering potential uncertainties relative to mass flows at the inventory level (that may also affect the LCIA results in terms of value loss).

Firstly, the shorter inaccessibility for Cu, Al, and Fe in tailings/landfills in waste scenario 1 results in a considerably lower value loss (−41%; Figure 5.5). Conversely, considerably larger value losses are observed (respectively + 42% and + 521%) when considering a longer inaccessibility for Cu, Al, Fe, Li, Mn, and graphite respectively as in the waste scenarios 2 and 3. Similarly, a much longer inaccessibility for resources emitted to the environment, by a factor 10 or 120 as respectively considered in the emissions scenarios 1 and 2, results in important increases in damage (respectively + 41% and + 537%), in particular driven by Al emissions.

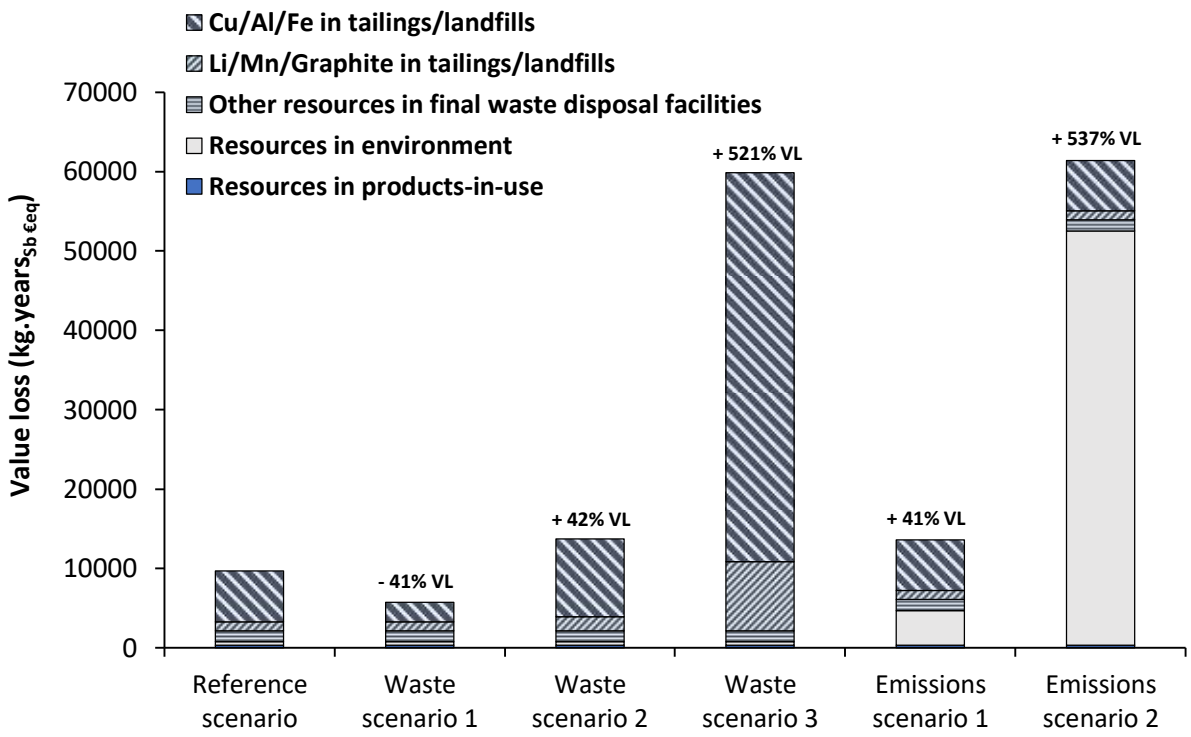


Figure 5.5 : Sensitivity of value loss to the duration of inaccessibility in dissipation compartments, considering the life cycle of a LiB for electric vehicles with the current EoL disposal scenario

It is noteworthy that the larger damage resulting from respectively 5 000 and 60,000 years of inaccessibility for all resources emitted to the environment is of relatively similar extent to that resulting from respectively 100 and 500 years of inaccessibility for a few resources in tailings/landfills. This raises the issue of temporal perspective. When considering a very long-term perspective (e.g., beyond 500 years), the accessibility to resources appears very uncertain given the current state of knowledge. This eventually offers limited room for further refining the inaccessibility duration of these resources (in particular those emitted to the environment) in the assessment. Instead, assumptions and scenarios about the recovery of resources embedded in waste stocks, and associated durations of inaccessibility, are less uncertain given the current state of knowledge (e.g., landfills and tailings whose reprocessing is currently under investigation; Hubau et al. 2020). Yet these durations need to be investigated further, offering potential room for further differentiation of resources inaccessibility as functions of the type of waste and resource in the impact assessment.

5.3.3 Operationalizing the JRC-LCI method in LCI databases: insights developed from 11 case studies

5.3.3.1 Replicability of the approach

The complete operationalization of the JRC-LCI method in LCA implies implementing the approach at the scale of full LCI databases. If considering the ecoinvent database, such operationalization would require covering thousands of LCI datasets, in particular by carrying out a RFA at the level of each associated single unit process. While accounting for resources is relatively straightforward with respect

to elementary flows (i.e., resource flows from ground or to the environment), it may be quite tedious in the case of resources embodied in intermediate input flows such as ancillary inputs (e.g., reagents, wear parts) or infrastructure (e.g., mining equipment). In particular, the quantification of resources in these intermediate flows calls for investigating background information (in ecoinvent reports), performing calculations or defining assumptions, which may be relatively demanding in terms of effort.

However, it is also noteworthy that, in the case of ecoinvent, each LCI dataset is constructed considering intermediate input flows that are also integrated in other datasets. For example, chromium steel appears as input in the inventories both associated with Cu and Mn ores mining; non-ferrous metal smelter is inventoried as infrastructure respectively for Cu, Ni and PGMs refining. In this study, RFA was carried out for 25 different ecoinvent unit processes, over 10 raw materials production systems (Table 5.2). Regarding seven raw materials (Cu, RE, graphite, Li, Mn, Ni, and PGMs), more than 64% of the mineral resource-containing intermediate input flows were found to be common to at least one of the other raw materials under study, while this number ranges from 25 to 50% with respect to the remaining raw materials (Table 5.5). This suggests that the large-scale implementation of RFA may be subject to a certain "snowball effect": the RFA for one unit process may build on previous RFA of other unit processes to account for resources embodied in intermediate input flows without repeating the whole procedure all over again. One may therefore imagine that the implementation of RFA may become more straightforward as the coverage in terms of unit processes increases.

Table 5.5 : Comparison of mineral resource-containing intermediate input flows for each raw materials production system considered in this study

Raw material	Total mineral resource-containing intermediate input flows in ecoinvent unit processes	% of intermediate input flows common to at least one of the other raw materials under study
Al Ingot	24	50%
Refined Co	25	32%
Cu Cathode	25	64%
Li_2CO_3	16	94%
Mn_2O_3	13	100%
Ni Class 1	6	100%
Refined PGMs	9	100%
RE oxides	19	74%
Si metal	4	25%
Graphite battery grade	9	89%

5.3.3.2 Integration of potentially dissipative flows in LCI computations: the ecoinvent case

The underlying approach for computing LCI results through the ecoinvent database relies on "matrix inversion to calculate accumulated system datasets (LCI results)" (Weidema et al., 2013). In particular, this builds on the following calculation approach:

The underlying approach for computing LCI results through the ecoinvent database relies on *"matrix inversion to calculate accumulated system datasets (LCI results)"* (Weidema et al., 2013). In particular, this builds on the following calculation approach:

Equation 5: $i = B(I_d - A)^{-1}.p$

Where:

- *i* = vector of dimension 1**n (elementary exchanges)*, reporting the LCI results associated with a given unit process;

- *B* = environmental matrix of dimension *n (elementary exchanges)* * *m (unit processes)*, depicting the direct elementary exchanges associated with one unit of output from each single unit process;

- I_d = Identity matrix of dimension *m*m;*

- *A* = technological matrix of square dimension *m*m (unit processes)*, reporting intermediate exchanges between unit processes;

- *p* = vector of dimension 1**m (unit processes)*, representing the inventory of direct intermediate exchanges associated with a given unit process (for which LCI results are calculated).

Incorporating potentially dissipative flows in the environmental matrix B would enable the accounting for dissipation in LCI calculations using ecoinvent datasets. This would entail an extension of the B matrix by *d* rows (flagged as "potentially dissipative flows") so that the matrix reaches a final dimension of *(n + d) * m*, with *d* representing the total number of predefined potentially dissipative flows of mineral resources. Assuming a total of *r* mineral resources and *c* dissipation compartments, *d* is the product of *r* and *c* (*d = r * c*).

In this study, c has been set to 3, distinguishing i) final waste disposal facilities, ii) environment and iii) products-in-use. Yet, as already discussed in Chapter 3 (Beylot et al., 2021), further subdivision in more compartments (e.g. differentiating several types of landfills as functions of the waste categories disposed of, several types of tailings to disposal facilities as a function of the ore mined, etc.) could offer further possibilities in terms of results interpretation and potentially more precise modelling of the severity of inaccessibility. This was out of scope in this study due to data constraints regarding the duration of inaccessibility in compartments. But this shall be further explored in the future both regarding the assets (e.g. level of details for results interpretation) and the constraints (e.g. data quality, nomenclature, data format, operationalization, etc.) it would imply for the approach.

5.3.3.3 Mass balance (in)consistency in LCIs

The implementation of the JRC-LCI method for deriving potentially dissipative flows requires consistent mass balances at the level of resources (ensured by RFA) throughout each unit process composing the product system. However, in the different case studies herein considered, many situations of inconsistent mass balance of resources were encountered using ecoinvent data. For instance, the amount of Al emitted to air as inventoried in the ecoinvent blasting dataset was found to be superior to the amount of Al embodied in the explosives (tovex), whose composition is reported in the dataset associated with its manufacture. In this case, to remedy this inconsistency and balance the difference between input and output flow, it was decided to set the input mass of Al equal to its output mass. Moreover, other cases of inconsistency where only input flows of resources (i.e., without corresponding output flows) are reported in the inventory data were also encountered. This accordingly required assuming an output flow corresponding to the input mass flow for the sake of

mass balance consistency, and an associated receiving compartment. For example, despite calcium is inventoried as input in the explosives manufacture in the associated dataset, no output flow is indicated in the blasting dataset (operation in which the explosive detonates, thus generating emissions of its embedded substances to the environment). This accordingly required assuming that the total mass of calcium embodied in the explosives is emitted to the environment. Furthermore, inconsistent balances were encountered with respect to resource flows within waste streams, and in particular in tailings, similarly to the case of Cu studied by Beylot et al. (2021), as developed in Chapter 3. This eventually required recalculating these mass flows using the mass balance equation.

The implementation of RFA at the unit process level, prior to deriving potentially dissipative flows, enables obtaining more complete, consistent, mass balances in LCI datasets, at the level of substances (resources). This improves data quality, not only regarding resources but more generally regarding all flows compiled at the unit process level. In this context, going beyond the first calculation approach implemented in this study through mass balance reconciliation at the substance level appears a particularly promising systematized approach to develop coherent LCIs along metal production process chains, including tailings generation and management (Beylot et al., 2022).

5.4 Conclusions and perspectives

The accounting for dissipative flows in LCIs, and associated severity of value loss in LCIA, offers new perspectives to address the damage to the safeguard subject for mineral resources. The applicability of the JRC-LCI method, and the potential insights it may bring to users, have been showcased considering 11 different case studies. The JRC-LCI method in particular allows for the identification of hotspots (in terms of life cycle steps) responsible for resource impacts all along the life cycle of a system (e.g., metallurgy and manufacturing processes, as well as EoL operations, identified as hotspots in this study), beyond the traditional depletion approach which rather considers mining operations as responsible for resource impacts. Moreover, the application of the JRC-LCI method to 25 LCI datasets (over 10 case studies) showed its potential for replication, in particular due to a certain “snowball effect” in the implementation of RFA. Full operationalization now depends on its implementation in LCI databases. We recognize that the coverage of thousands of LCI datasets in the case of the ecoinvent database would require significant efforts. But we advocate for such a change, as this would (i) support more resource-efficient decision-making, e.g., especially when combined with CFs as those developed in this study, and (ii) result in higher quality of LCI datasets through balanced inventories, which would therefore contribute to the improvement of environmental impact indicators beyond resource issues.

The herein proposed impact assessment approach enables assessing the severity of mineral resources dissipation, by capturing the inaccessibility of resources (through the integration of durations of inaccessibility in the characterization model) as well as value loss (through resource prices, building on Chapter 4; Ardente et al., 2023). However, major rooms for improvement still remain regarding these durations, which were based on relatively uncertain estimates in this study. Further refining of these durations of inaccessibility therefore appears necessary for ensuring a higher level of confidence in this impact assessment approach in the future, in particular through further refining the short- and mid-term inaccessibility of resources (< 100 years) embedded in final waste disposal stocks, for which future recovery (through, e.g., landfill/tailings mining) is currently actively explored. This may additionally come along with potential differentiations of inaccessibility durations as a function of the resource considered.

Finally, “occupation-in-use” of resources in the technosphere was considered out of scope in this study, similarly to Beylot et al. (2021; Chapter 3) who justified that it does not contribute to dissipation,

but rather to inaccessibility. Yet, it is acknowledged that the inaccessibility-based impact assessment approach herein presented appears adapted to comprehensively capture the reduction in accessibility resulting from both potential dissipation and occupation-in-use. It is however noteworthy that when occupied-in-use, a resource still provides a function and accordingly holds a value to users, which therefore implies that it is, by definition, still accessible to some humans. This calls for differentiating the inaccessibility induced by occupation-in-use from that induced by the potential dissipation of resources in this LCIA approach, which will require additional developments in the characterization model as developed so far.

6 Chapter 6 – Discussion of the JRC-LCI and JRC-LCIA methods in perspective with other methods to address mineral resources depletion, dissipation and accessibility in LCA

This Chapter is essentially drawn from:

Beylot, A., Dewulf, J., Greffe, T., Muller, S., Blengini, G.-A. 2023. Mineral resources depletion, dissipation and accessibility in LCA: a critical analysis. Submitted to the International Journal of Life Cycle Assessment.[4]

Contribution of the co-authors:

- Antoine Beylot: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.
- Jo Dewulf: Conceptualization, Methodology, Investigation, Writing - review & editing.
- Titouan Greffe: Conceptualization, Methodology, Investigation, Writing - review & editing.
- Stéphanie Muller: Conceptualization, Investigation, Writing - review & editing.
- Gian-Andrea Blengini: Conceptualization, Investigation, Writing - review & editing.

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6.1 Introduction

In the recent years, in parallel to, or after, the UNEP GLAM2 review and recommendation work, several methods have been developed to address reduction of resource accessibility and resource dissipation (i.e. full inaccessibility) in LCA, both at the LCI and LCIA levels; namely EDP (van Oers et al., 2020b), ARP (Owsianiak et al., 2022), ADR/LPST (Charpentier-Poncelet et al., 2021; 2022c), and JRC-LCI (Chapter 3; Beylot et al., 2021), complemented by JRC price-based (Chapter 4; Ardente et al., 2023) to capture value loss. Comparatively, methods related to depletion, future efforts, thermodynamic accounting, and to a lower extent supply risks, received in the meanwhile less emphasis from the scientific community (in scientific literature and conferences), and from standardization/harmonization initiatives (e.g. in the PEF context, towards potentially delivering new recommendation).

Moreover the depletion-based ADP method has been and is extensively implemented in daily LCA practice, in particular thanks to adapted standard LCI databases (e.g. ecoinvent) and LCA software (e.g. SimaPro) that enable easy calculations. This extensive implementation may however be opposed to the by far less extensive discussion of the core concepts and assumptions the ADP method is grounded on. Existing review works described the method, its underlying data, assumptions and modelling concepts (e.g. Sonderegger et al., 2020; Schulze et al., 2020b). But more than 20 years after this publication, an in-depth critical analysis is still needed.

This chapter aims at critically analysing these recent resource-dissipation (or -accessibility) based methods, under the lens of criteria inspired and derived from the analysis in UNEP GLAM2 (Sonderegger et al., 2020). It similarly reviews the ADP (depletion-based) method, which is the reference LCIA method in daily LCA practice. This article firstly describes the characteristics of these methods (section 6.2 and Appendix E), and then performs an in-depth analysis including discussion on strengths and limits (section 6.3). It gives an overview of the methods' relevance to the safeguard subject, model robustness, data quality and completeness, and operational capabilities (sections 6.3 and 6.4). It particularly intends i) to discuss assumptions and modelling choices from a user perspective (LCA practitioners and decision-makers), and ii) to highlight and discuss the scientific-evidence and scenarios on which they build.

6.2 Methods analysed: identification and general characteristics

This section firstly describes the methods reviewed, in terms of: concept, target, resource flows in scope, impact mechanism, and temporal scope; as summarized in Table 6.1 and Figure 6.1, and more extensively explored in Appendix E.

Table 6.1 : Synthesis of main characteristics of six methods to address mineral resource use in LCA

Method	Reference	Concept captured	Compromising actions covered in the addressed concept of dissipation (as per definition of Dewulf et al., 2021)	Practical implementation in LCA context	Temporal scope	LCI resource flows to which CFs apply		Number of CFs and form of resources	Unit
						Main (tested in literature)	Potential, yet not tested (claimed in literature, column "Reference")		
ARP	Owsianiak et al., 2022	Dissipation	Emitting to environment	Classification of dissipative flows in LCI	Very long term to infinite	NA	NA	NA	NA
JRC-LCI	Beylot et al., 2021	Dissipation	Emitting to environment Landfilling Disposal of tailings Downcycling	Addition and classification of dissipative flows in LCI	Short-term	NA	NA	NA	NA
JRC-LCIA	Ardente et al., 2023	Value Loss (when combined with JRC-LCI)	NA	CFs multiplied by inventory flows	Short-term	Dissipative resource flows as in JRC-LCI method	Resources from ground. Or dissipative resource flows to environment as in ARP	66 chemical elements and minerals	kg $Cu._{€eq}$/kg
ADP ultimate reserves	Last update in van Oers et al., 2020a	Depletion	NA	CFs multiplied by inventory flows	Very long term to infinite	Resources from ground	NA	76 chemical elements	kg Sb-eq./kg
EDP	van Oers et al., 2020b	Dissipation	Emitting to environment	CFs multiplied by inventory flows	Very long term to infinite	Emissions to environment	NA	76 chemical elements	kg Cu-eq/kg
ADR and LPST	Charpentier-Poncelet et al., 2022c	Dissipation (midpoint) Value Loss (endpoint)	Emitting to environment Landfilling Disposal of tailings Downcycling	CFs multiplied by inventory flows	Short-term and long-term	Resources from ground	Dissipative resource flows	61 chemical elements	kg Cu-eq/kg

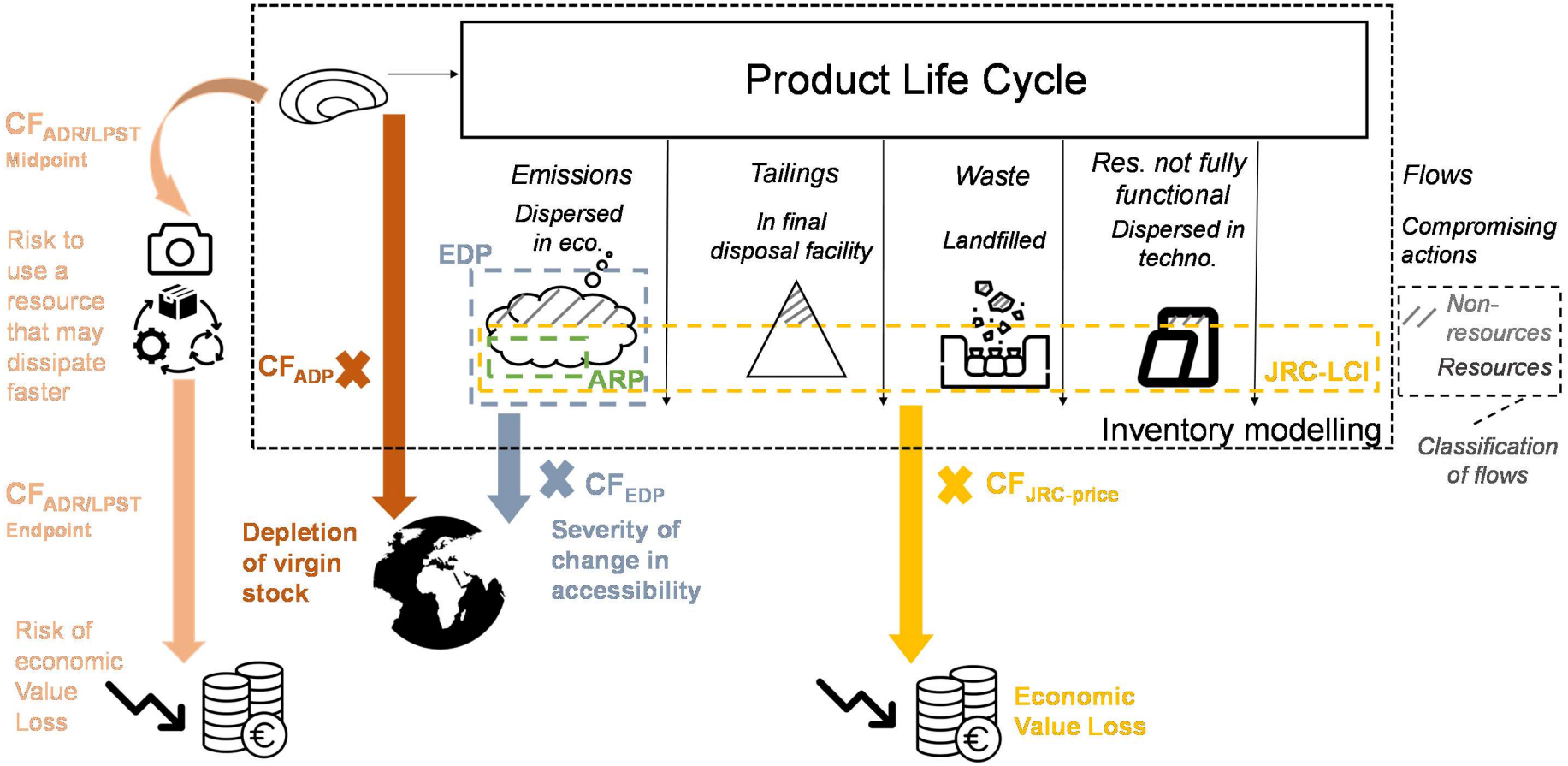

Figure 6.1 : Implementation of dissipation- and depletion-based methods to address mineral resources use in LCA: generic framework. Terminology of concepts captured is based on our interpretation of the methods, which may deviate from that of the original publication (e.g. regarding ADR/LPST in Charpentier-Poncelet et al., 2022c). res.: resources; eco.: ecosphere; techno.: technosphere)

6.2.1 Short description

The Abiotic Depletion Potential method, ultimate reserves ($ADP_{ultimate\ reserves}$; van Oers et al., 2020a), is intended to capture the issue of mineral resource depletion; i.e. the contribution to exhaust the natural stock of a non-renewable resource, in turn limiting its availability to future generations. The Average Dissipation Rate (ADR) and Lost Potential Service Time (LPST) methods are grounded on the concept of service time of resources, which is the duration over which resources provide a service within the economy, from their extraction from ecosphere until dissipation after one or several uses (Charpentier-Poncelet et al., 2022c). ADR and LPST are two different methods: ADR CFs correspond to rates (by definition), while LPST is a distance-to-target method in which the target is defined as an optimum service time. They are essentially derived from the same concepts, assumptions and resulting values, averaged considering current conditions. Consequently in the following they are essentially discussed as one single method ("ADR/LPST").

Moreover, the Environmental Dissipation Potential (EDP; van Oers et al., 2020b) method by definition captures dissipation to the environment. All emissions to environment are considered dissipative flows, with EDP CFs that aim at accounting for the severity of this dissipation. The ARP (Abiotic Resource Project) method (Owsianiak et al., 2022) further enables to classify an emission of a metal to the environment as dissipative, or not, at the LCI stage of a LCA. Moreover the JRC-LCI method consists in reporting dissipative flows of mineral resources at the unit process level, in mass units (Chapter 3; Beylot et al., 2021), considering a predefined list of dissipative mineral resource flows to a number of dissipation (receiving) compartments. In the short-term perspective (25 years) suggested to be considered, any flow of resource to i) environment; ii) final waste disposal facilities (landfills and tailings final disposal facilities); and iii) products-in-use in the technosphere, in which the resource is no longer fully functional, is to be reported as dissipative at the unit process level. Finally the JRC price-based method is an impact assessment method which builds on the price of resources, considered as a proxy for the multiple, complex and varied functions they can have for diverse economic sectors (Chapter 4; Ardente et al., 2023). It was initially developed to capture the value lost as a result of mineral resources dissipation.

6.2.2 Concepts captured, and influence of temporal scope considered

Out of the six methods reviewed, four intend to address the concept of mineral resources dissipation (ARP, JRC-LCI, EDP and ADR/LPST; Table 6.1) while one addresses depletion ($ADP_{ultimate\ reserves}$). The JRC-LCI and ADR/LPST methods both consider the same compromising actions (emitting to environment, landfilling, disposal of tailings and downcycling), and resulting dissipative flows (Table 6.1 and Figure 6.1); in particular both building on the same definition of the concept of "dissipation" (Beylot et al., 2020a; 2020b). They are however fundamentally different in that the JRC-LCI method requires to report dissipative resource flows at the LCI level, while the ARP/LPST methods embed the potential dissipative nature of resource flows within CFs. The latter i) are derived from an average snapshot of the current status on dissipation and resources lifetimes in the economy (not specific to the product/system lifecycle; e.g. 7 years of average duration over which lithium remains in use in the economy after extraction; 45 years regarding copper, 154 years regarding iron, etc.; Charpentier-Poncelet et al., 2022b), and ii) apply to the resources extracted from ground as induced by (and specific to) the product/system lifecycle.

Moreover, the ARP and EDP methods consider a very long-term (to infinite) perspective. This eventually results in the coverage of a more limited set of compromising actions and resulting dissipative flows (emissions to the environment only) as compared to the JRC-LCI and ADR/LPST methods (which include dissipative flows within technosphere).

Finally, the JRC-LCIA method is neither based on the depletion nor on the dissipation concepts, but instead on the user value that the current and past generations attribute to metals and minerals, which also reflects market expectation for the coming years. It was initially developed to be used in combination with the JRC-LCI method, in order to capture (through price-based CFs) the value of mineral resources lost as a consequence of their loss in physical (mass) terms.

6.2.3 CFs and inventory flows

Four of the reviewed methods are LCIA methods ($ADP_{ultimate\ reserves}$, ADR/LPST, EDP and JRC-LCIA) which developed a set of CFs applicable to a relatively large number of mineral resources (from 61 to 76, depending on the method; Table 6.1). Three of these sets of CFs were developed to be applied with current standard LCI datasets ($ADP_{ultimate\ reserves}$, ADR/LPST, and EDP). CFs associated with $ADP_{ultimate\ reserves}$ and ADR/LPST apply to inventory flows of primary resources extracted from ground, as reported in current LCI datasets and databases (e.g. ecoinvent or Environmental Footprint; EF). They however address the contribution of a given product/system to different issues associated with mineral resources, respectively depletion ($ADP_{ultimate\ reserves}$) and dissipation (ADR/LPST). EDP is also a LCIA method, with CFs that apply to current LCI datasets. In that case however EDP CFs apply to flows of emissions to environment, considered dissipative flows in the method.

Finally, the fourth reviewed LCIA method (JRC-LCIA) enables to capture the value lost as a result of dissipative resource flows induced by a product or system along its life cycle, in combination in particular with the JRC-LCI method. It may however also apply to resources flows extracted from ground, as reported in current LCI databases. Moreover, extension of the ADR/LPST methods from midpoint to endpoint is based on price indices (ratio of the price of one metal over the price of a reference metal; Charpentier-Poncelet et al., 2022c), conceptually very similar to the price-based CFs of the JRC-LCIA method. The major difference relies on the way these CFs are applied: respectively directly on dissipative resource flows as reported in LCIs (JRC price-based CFs combined with JRC-LCI method; in Chapter 4 and Ardente et al., 2023), or in combination with midpoint ADR and LPST CFs which apply to resources extracted from ground in LCIs (in Charpentier-Poncelet et al., 2022c).

Two of the reviewed methods (ARP and JRC-LCI) have instead not developed a set of CFs to be multiplied with inventory flows. On the one hand ARP is a “classification method”: building on existing LCI datasets, it intends to support in identifying whether some inventory flows of metals are dissipative or not. It considers a very long-term to infinite temporal perspective, and subsequently covers only “emitting to environment” as a compromising action (i.e., focusing on emissions to environment). On the other hand the JRC-LCI method instead considers a short-term perspective (25 years) and as a consequence additionally covers compromising actions that lead to dissipative resource flows within technosphere (final disposal and non-functional recycling). The JRC-LCI method is therefore a method that both i) classifies flows as dissipative or not (e.g. in the case of flows of emissions to environment, yet with a different approach than that implemented in ARP), and ii) requires to compile dissipative resource flows within technosphere (e.g. to tailings final disposal, to landfills, etc.) at the LCI stage, at the unit process level. So far, these dissipative resource flows have not been reported in LCIs classical compilation practices, including in standard LCI databases (e.g. ecoinvent or EF).

6.3 In-depth analysis of methods: results and discussion

6.3.1 ADP Ultimate Reserves

6.3.1.1 Model, data and resulting CFs

$ADP_{ultimate\ reserves}$ CF associated with a given chemical element *i* is calculated as the ratio between the annual world production of this element (P) and its ultimate reserve (R, squared); P/R^2; this divided by the same ratio for one reference substance (antimony). ADP CFs are expressed in units of kg Sb-eq./kg. Considering the *ultimate reserve* (based on crustal content) instead of the *ultimately extractable reserve* (the total amount of resources that might be extracted by humans) has several implications, including the fact that it "*implicitly assumes that the ratio between the [two] is equal for all resource types"* (van Oers et al., 2020a).

The ratio P/R^2 builds on two sets of data: i) data for primary production, primarily drawn from reports of reference geological surveys; and ii) data from Rudnick and Gao (2014) on concentrations of the upper continental crust, with assuming a 12 km depth (in a context where the deepest mines in the world currently have a depth of 4 km, van Oers et al., 2020a). CFs are available for 76 chemical elements in the updated ADP version published by van Oers et al. (2020a). Since its first publication in 1995, the ADP method has been updated twice, considering updated data on annual production (in 2002 and 2020), and updated data on annual production and ultimate reserve (in 2020). This implied in parallel a wider coverage of mineral resources, from 48 to 76. The CFs are representative of a snapshot of potential impact of production in 2020 to the reserves in the earth's crust.

6.3.1.2 Key strengths and limits

The $ADP_{ultimate\ reserves}$ method enables to address the question: "*How can I quantify the relative contribution of a product system to the depletion of mineral resources?*" (Berger et al., 2020). It is based on available and essentially robust data on the concentration of chemical elements in the earth crust and annual production. Crustal content is acknowledged as a "*stable, comprehensive dataset*", making it the best option for attempting a physical estimate of abiotic resources depletion, if the goal of the LCA is addressing depletion (Drielsma et al., 2016). The same authors argue however that opportunity cost approaches are more applicable in the context of understanding minerals availability. Calculations are based on average data for the upper earth crust, so that the adopted earth crust's depth, area, and density have only limited influence on the relative calculated crustal content (van Oers et al., 2020a).

It is recommended both by the UNEP Life Cycle Initiative (GLAM2), and in the context of the PEF (Berger et al., 2020; Zampori and Pant, 2019). It is easy to implement with classical LCA software and LCI databases. The coverage of chemical elements (76 in total) is fairly comprehensive. It has been widely used in the past decade, with numerous applications to case studies. Finally, the update on the crustal content (in 2020 compared to the original version published in 2002) had a limited effect on CFs (van Oers et al., 2020a).

If the crustal stock is rather stable, conversely production data are not. Subsequently, the proposal for a change from production data for one given year to production data cumulated over a longer period, had a larger influence (van Oers et al., 2020a). Factors of difference between CFs before and after update were similar for some chemical elements (e.g. factor 16 for cobalt, 15 for copper, 13 for nickel, etc.) which may eventually lead to important differences in total impact but limited influence in terms of relative contributions. For some elements the difference was large (e.g. platinum group metals,

PGMs, with a factor 441 of increase, lithium with a factor 2), potentially having large influence on (relative) impacts. The ADP developers' recommendation of now basing CFs on cumulative productions over the period 1970-2015 however limits sensitivity to future short-term updates (van Oers et al., 2020a).

One may highlight that whereas the computation of $ADP_{ultimate\ reserves}$ CFs would require to use mineral commodity data for *extraction* (at the mining level), production values of e.g. Cd, Ge, In, Se and Te are instead approximated with data relative to *refinery production* drawn from United States Geological Survey (USGS) reports. As an example, the reported refinery production of indium in 2011 amounts to 662 tons (USGS, 2014), while its extraction amounts at least to 1 216 tons (Licht et al., 2015); that is a factor 1.8 of difference. The implementation of this proxy for some resources accordingly introduces a bias, whose effect on the resulting uncertainty of CFs would still need to be discussed and reported. More importantly, we hereafter discuss how far ultimate reserve is an adapted metric to address impact of mineral resources use in a LCIA method.

i) *How far mineral resources get depleted once extracted from the ground?*

Mineral resources, especially for what concerns metals, are transformed, but do not "disappear". Instead they are transferred from some stocks to some others, with various degrees of quality and/or accessibility for future use (Dewulf et al., 2021), as also acknowledged and captured in the extended abiotic depletion potential (AADP) method including anthropogenic stocks for the assessment of resource depletion (Schneider et al., 2015). How far a given product system alters mineral resources therefore relates to how far it reduces their quality and/or accessibility within the technosphere and potentially from the technosphere to the ecosphere. How far the geological stock gets exhausted (depleted), as a result of this product system lifecycle, is conversely of limited concern.

ii) *How far ultimate reserve is an acceptable substitute for ultimately extractable reserve?*

We agree with the ADP developers when they state that "*the concentration-presence distribution will most likely be different for each resource*" (van Oers et al., 2020a). As a consequence, it is questionable to assume that "*the ratio between the ultimately extractable reserve and the ultimate reserve is equal for all resource types*", which is core in the $ADP_{ultimate\ reserves}$ method. The potential for extracting a resource in the future, whether from a secondary or from a primary stock, depends on a multitude of parameters, including e.g. the concentration of metals in a primary mineral deposit, which remains an anomaly of the earth crust, with little, if none, connection with the average crustal concentration. It is impossible, at least with current data, knowledge and capabilities, to demonstrate that the ultimately extractable reserve will be proportional to the current continental crustal content as assumed at the basis of the ADP method.

ADP CFs are therefore based on data that, despite essentially robust, do not fully capture what they are intended to. The deviation between the estimate (ultimate reserve) and what it is intended to represent (ultimately extractable reserve) is not quantified; because it cannot. As a conclusion, $ADP_{ultimate\ reserves}$ CFs miss accuracy, despite inaccuracy (potentially, large) is not quantifiable. It is particularly noteworthy that current methods to estimate extractable global resources (EGRs) or closely related concepts such as ultimate extractable reserve are considered by some author *"so uncertain as to render them generally unfit for guiding policy with regard to resource depletion and governance*" (West, 2020).

In such a context, an important and concrete contribution is led by the United Nations Economic Commission for Europe (UNECE), in collaboration with intergovernmental institutions, governments and multiple stakeholders, and aims at developing and applying the United Nations Framework Classification for Resources (UNFC, 2019). The main goal of UNFC is to classify and rank mining and recycling projects according to levels of feasibility, thus substantially contributing to a better understanding on how the current stock of reserves will likely expand in the future and progressively incorporate natural or anthropogenic stocks that can currently be classified as resources.

The UNFC is a concrete step forward to characterize accessibility to resources for current and future generations, though it will never target depletion in association to crustal content, which will remain of limited interest for those who want to contribute to resource accessibility.

iii) How far only continental crust shall be considered to quantify ultimate reserve as a *substitute for ultimately extractable reserve?*

Inaccuracy is further increased in the way ultimate reserve is estimated. In the $ADP_{ultimate\ reserves}$ CFs calculation, only continental crust is considered. Meanwhile, ADP developers acknowledge that "*if mining of the crust beneath the oceans is considered feasible, oceanic crust could become important*." (van Oers et al., 2020a). At this stage of current knowledge, it is not feasible to estimate the extent to which oceanic crust will be exploited in the far future; but one may envisage that it will (at least, partly) be, in a context where comparison of deep-ocean mineral deposits with land-based resources appears promising for some metals (Hein et al., 2013). The same goes for space mining: in-situ resource utilization is considered among opportunities for space exploration and utilisation by some countries (CSIRO, 2018). In both cases (oceans and extra-terrestrial resources from e.g. the Moon, Mars, or Near-Earth Asteroids) there is no possibility to predict how far these resources will be exploited by humanity over the very long-term to infinite scope considered in the $ADP_{ultimate\ reserves}$ method. Their potential exploitation may only be discussed, and somehow assessed through scenarios, e.g. building on techno-optimism (Moore et al., 2022).

As a conclusion, we argue that the ultimately extractable reserves, ultimate reserves and resulting $ADP_{ultimate\ reserves}$ are very sensitive to unknowns on: i) which stocks shall be considered (continental crust, oceanic crust, and/or space), and ii) how far these will actually be exploited. By definition of unknowns, $ADP_{ultimate\ reserves}$ are therefore sensitive to very uncertain parameters.

iv) How far availability of resources in the earth crust is a relevant metric to support decision making?

It is recalled that it is not the intention of the ADP developers to consider the global amount of resources in the earths' crust as the ultimately extractable reserve that becomes depleted. In $ADP_{ultimate\ reserves}$, ultimate reserve is considered a relevant (proportional) substitute for ultimately extractable reserve. Such an assumption on the proportionality between the two is debatable, as discussed above. It may therefore be tempting for some LCA practitioners to assume that depletion is quantified through ADP CFs based on ultimate reserve, considering crustal content, as the ultimate reservoir of concern. This would be an unrealistic assumption, as most of a given metal or mineral contained in the earth's crust "*with high certainty will remain forever uneconomic to mine"* (Tilton et al., 2018; here referring to copper). As stated by Scholz and Wellmer (2021), "*it is not the physical existence of a raw material that is important but the cost for extracting and converting it into a useable product*". Furthermore, it is noteworthy that if crustal content had been a relevant metric, it would have implied that resource

depletion is only a minor issue (if an issue at all) to be considered in decision-support methods like LCA. Given huge physical quantities in the earth at current production rates (e.g. 84 million years of copper and 7.7 billion years of aluminium; Tilton et al., 2018), physical existence (availability) in the earth is not a pressing problem to address; contrarily to other environmental issues addressed through LCA indicators (e.g. climate change). Impact of resource use on the Area of Protection "natural resources" is likely a relevant issue to be addressed in LCA; yet not with the $ADP_{ultimate\ reserves}$ method.

6.3.2 EDP

6.3.2.1 Model, data and resulting CFs

The operationalization of the SUPRIM conceptual framework through EDP for a very long-term perspective is based on a number of assumptions and choices (explored in Appendix E), including in particular:

- continental crustal content is used as a proxy for the accessible stock in the environment and technosphere (similarly to the approach undertaken in the ADP method);
- hibernation in technosphere is considered to be negligible, due to economic and technological developments that will make the hibernating stocks accessible over the very long term;

The authors claim that these assumptions correspond to a scenario that "*will happen at some point in the far future*" (van Oers et al., 2020b), with explicitly excluding any precise timeframe for the completion of this scenario (e.g. 100 years, 1000 years, or even more). Eventually only environmental dissipation is considered as relevant in this context.

Several additional assumptions are made in the development of EDP CFs, including in particular:

- stock variation for one resource *i* over the very long-term, due to dissipation to environment as the compromising action, is calculated assuming that primary production at present (in mass) is equal to emissions to environment (in this very long-term);
- severity associated with the dissipation of a given mass of resource *i* is quantified through the ratio P_i / R_i^2, also used in the ADP CFs. The authors additionally mention that other metrics may be used to assess severity (e.g. exergy, prices, stocks, etc.)

These hypotheses eventually imply that EDP CFs are equivalent to those of the $ADP_{ultimate\ reserves}$ method regarding elements, still i) with EDP CFs expressed in kg Cu-eq while ADP CFs are expressed in kg Sb-eq (factor 36.41 of difference between the two sets of CFs), and ii) with correction factors in case of substances, in a context where EDP CFs apply both to chemical elements and substances. These CFs shall be applied to emissions to environment by LCA practitioners, entirely considered as dissipative flows in the EDP method. CFs for 76 chemical elements are available (Table 6.1), and additionally developed for more than 1 000 elementary flows of substances emitted to air, soil and water.

6.3.2.2 Key strengths

The EDP method enables practitioners to address the decrease in accessibility of mineral resources induced by product systems, through quantifying these systems' contributions to dissipation to the environment. CFs are comprehensive and based on essentially robust data, similarly to $ADP_{ultimate\ reserves}$ CFs. The EDP method has a high level of operability in combination with standard approaches for LCI modelling, given that CFs apply to emissions to environment as classically accounted for in LCI datasets (e.g. in ecoinvent or EF). The SUPRIM conceptual framework that is operationalized in a very long-term

perspective in the EDP method may furthermore also be applicable to other temporal perspectives in case data are available.

6.3.2.3 Key limits

The EDP method is however based on a relatively large number of assumptions aimed at operationalization. In the following, the most disputable assumptions at the core of the calculation of EDP CFs are discussed.

As a more minor weakness of the EDP method, it is to be noted that it applies to all emissions to environment, that is including also emissions of the share of elements that are "non-resources" (e.g. emission of copper from coal combustion to the environment is not an emission of a mineral resource; Chapter 3 and Beylot et al., 2021). The EDP CFs are also calculated considering that all elements in the crust are resources (including e.g. copper in coal), which makes the EDP method overall consistent on this aspect between inventory (of dissipative resource flows) and impact characterization.

We moreover identify three debatable issues with the EDP method.

i) Is hibernation a negligible issue for resources accessibility compared to environmental dissipation?

The EDP method developers state that *"hibernation is assumed to be negligible due to the assumption that economic and technical developments will successfully make hibernating stocks accessible on the very long term"* (van Oers et al., 2020b). One could instead mention a multitude of examples of hibernating stocks for which it is highly probable that the resources they contain will never be recovered with the original functionality being fully preserved, even in favourable contexts of technological and economic developments; e.g.:

- metals in incineration bottom ashes used in road construction;
- metallurgical slags landfilled, which in particular contain some metals which are not economically and technologically extractable in current conditions, and for which it is unreasonable to imagine any slag landfill mining in the future. One may mention more specifically rare earths elements in permanent magnets of hard disk drives, which are so far mainly derived to classical metallurgy without any recovery (i.e., ending into slags) despite the existence of some processes, not at industrial scale though, for their recovery (Beylot et al., 2020c);
- any alloying element from specialized steel non-functionally (or poorly functionally) downcycled as tramp element to ordinary steel; or more generally any "spice metal" in alloys (Graedel and Miatto, 2022). These flows are resource flows dispersed into the technosphere from downcycling, whose duration of inaccessibility is anticipated by Dewulf et al. (2021) to be at least 500 years (as best estimate), similarly to flows dispersed in the environment.

Many more examples may be cited. We acknowledge that landfill mining and reprocessing of tailings are practices that exist; but that are implemented to a limited extent only, e.g. in the EU (Blengini et al., 2019), and still face economic, technical and environmental challenges (Sarker et al., 2022). There are numerous examples of resources still embodied in landfills, tailings final disposal, and in products (as non-functional elements) far beyond some decades after their disposal. One may in particular note that thousands of years after primary mining exploitation, mining waste still contain resources so far not extracted; e.g. on sites such as Plombières in Belgium or Salsignes in France. It can reasonably be

assumed that accumulated hibernating stocks (currently generated) will be recovered with higher efficiency than those generated during the Roman Age. Yet, given current knowledge and practice, in particular in terms of 1) very low End-of-Life (EoL) recycling rates for many metals (UNEP, 2011), 2) limited industrial development of landfill mining and tailings reprocessing so far, in particular in the EU (Blengini et al., 2019), and 3) anticipated durations of inaccessibility of metals in landfills and tailings disposal facilities (Dewulf et al., 2021), it seems particularly debatable to consider the phenomenon of hibernating stocks as short-term phenomena "*negligible over the very long term*" (van Oers et al., 2020b). In this context assuming that the entirety of hibernating stocks of resources (including in landfills and tailings disposal facilities) will be extracted is uncertain, and most probably very unrealistic. Paraphrasing Tilton et al. (2018) stating that "*most of [the copper contained in the earth's crust] with high certainty will remain forever uneconomic to mine*", we argue that part of the resources contained in hibernating stocks *with high certainty will remain forever uneconomic to mine*.

The assumption on the negligible nature of hibernation in a very long-term is therefore critical in EDP CFs development. One could actually imagine a continuum of other assumptions regarding future capacities to extract resources from hibernating stocks, for many of them at least as acceptable. It is key to highlight that EDP CFs are therefore based on one prospective scenario, in no way predictive and based on optimistic techno-economic considerations. Other scenarios, building on various assumptions, would lead to (sometimes, very) different coverage of dissipative flows.

ii) How far ultimate reserve is an acceptable substitute for ultimately extractable reserve?

van Oers et al. (2020b) assume that *"for the very long time frame (e.g., 100 years, 500 years, or more) […] the ultimately extractable element stock will asymptotically approach some critical portion of the total available resource in the environment".* They additionally state that: *"for a relative assessment of the contribution of the use of different resources […], the continental crustal content is suggested as an acceptable proxy […]".* We recall that similar assumptions are made at the basis of the $ADP_{ultimate\ reserves}$ method. We consider that these assumptions are most probably inappropriate, as discussed in section 6.3.1 relative to $ADP_{ultimate\ reserves}$ CFs.

iii) Is LCI modelling (for implementation of EDP CFs) fully consistent with EDP CFs computation?

Finally, we argue that the EDP method is based on contradictory assumptions regarding calculation of CFs and inventory modelling. The continental crust (with 12 km depth) is set on the one hand as the basis for the calculation of the ultimate reserve used for the computation of EDP CFs. On the other hand, in the LCI step, emissions to environment are considered irreversibly inaccessible. Yet an important part of emissions to environment will end in soils, as either directly emitted to soil or ending in soil after having been emitted to air or water. That is to say, an important share of emissions to environment end in what van Oers et al. (2020b) consider the (accessible) ultimate reserve in EDP CFs computation; whereas they are (inconsistently) considered dissipative (i.e. inaccessible) in LCI modelling recommended for EDP implementation.

6.3.3 ARP

6.3.3.1 Model, data and resulting approach to inventory

The ARP method aims at improving the consideration of environmental dissipation in the EDP method by relying on two criteria (Owsianiak et al., 2022). Firstly criterion A is intended to determine "*whether an emission flow actually contributes to loss of accessibility of the emitted element […] over the relevant time frame"*. This criterion applies to all global anthropogenic emissions, occurring at present and in the future. Considering the environmental mechanisms governing the fate of the emitted element, resulting concentration at steady state is calculated and compared with a "*reference concentration*", intended to represent "*what is accessible for humans within the considered time span*". The authors set this reference concentration as the average elemental concentration in the upper continental crust.

Secondly criterion B is intended to determine "*whether the metal in a dissipative emission (according to criterion A) originates from a source that would be considered a mineral resource*". Similarly to the case of criterion A, the associated *"reference concentration"* is also set as the average elemental concentration in the upper continental crust. The ratio of concentration in the source to the reference concentration is calculated for each source-element combination in order to set whether the element is a resource, or not. This calculation of ratios is further completed with some assumptions; e.g. any element present in any ore is considered a mineral resource, i.e. assumed to be accessible in the long term irrespective of its concentration level in that ore.

Regarding 23 chemical elements, average elemental concentration in the upper continental crust is drawn from Rudnick and Gao (2014), that is also the data used to update $ADP_{ultimate\ reserves}$ CFs (van Oers et al., 2020a) and to derive EDP CFs (van Oers et al., 2020b). Steady state concentrations in the environment as a result of global anthropogenic emissions are calculated from the multimedia fate module of USEtox® 2.1 (version LC-Impact). Concentrations of metals in source oil and coal are drawn from the literature (e.g. Rauch and Pacyna, 2009).

Coverage is extended from 23 to 65 elements in total through a "*stepwise approach*", consisting in a set of assumptions particularly for those elements for which multimedia fate models are not yet available (building on general conclusions drawn from the 23 elements), and regarding the resource nature of these elements depending on their source. The ARP method (Criterion A only) is additionally combined with available EDP CFs, delivering 65 CFs for metals and metalloids (Owsianiak et al., 2022).

6.3.3.2 Key strengths

Similarly to the EDP method, the ARP method enables LCA practitioners to address the decrease in accessibility of mineral resources induced by product systems, through quantifying these systems' contributions to dissipation to the environment. It intends to improve further the EDP method, by capturing (through a criterion-based approach) those emissions that are indeed emissions of "*mineral resources*". This is particularly relevant in a context where the definition of mineral resources in LCIs has been so far poorly discussed in the literature. For example, mineral resources accounting in LCI of primary metals production, including tailings management, is classically inconsistently combined with some depletion-based impact assessment method (Beylot et al., 2022). The ARP method is moreover operationalized in combination with existing EDP CFs, covering a fairly large number of chemical elements (yet only considering one out of the two ARP criteria). Finally it is based on robust data of continental crustal content, similarly to ADP and EDP CFs.

6.3.3.3 Key limits

The ARP method relies in the meantime on a number of fundamental, disputable, assumptions.

i) *Is technosphere hibernation a "relatively short-term [phenomenon] (acting at time scales of less than a year to decades)"?*

The ARP developers consider environmental dissipation as *"relevant for both short- and long-term time horizons (time scales of centuries)",* while they "*[see]" "occupation in use and technosphere hibernation as relatively short-term phenomena (acting at time scales of less than a year to decades)"* (Owsianiak et al., 2022). Instead, one could mention a multitude of examples of hibernating stocks for which it is highly probable that the resources they contain will never be recovered with full functionality, even in favourable contexts of technological and economic developments. Similarly to the case of the EDP method, we argue here that part of the resources contained in *hibernating stocks with high certainty will remain forever uneconomic to mine* (see section 6.3.2.3 "Key limits" dealing with the EDP method). The focus on environmental dissipation in ARP is therefore debatable, and eventually potentially misleading.

ii) *Does the average element concentration in the upper continental crust correspond to any "average condition" or "best estimate" below which mineral resources can be reasonably considered inaccessible?*

The choice for average crustal concentration as "*the threshold below which mineral resources can be reasonably considered inaccessible*" (i.e., "*which determines whether a given environmental matrix has a real potential to be a source of metal resources for humans in the long-term*"; Owsianiak et al., 2022) is fundamental in the ARP method, but it does not build on any scientific evidence or on any real (e.g. industrial) data. This is the ARP developers' best guess for threshold, and does not correspond to any agreed "*average condition*" or "*best estimate*". Despite this guess is valuable, a very large number of other best guesses may have been made, most probably at least as valuable as the one at the core of the ARP method. This threshold is therefore most probably inaccurate, with its associated level of inaccuracy being uncertain but expected to range from moderate to very high.

iii) *Are emissions occurring in product life cycles all dissipative as considered in EDP, or instead not all dissipative as considered in ARP? Accordingly, may EDP and ARP methods be consistently combined?*

ARP and EDP methods may be used independently, or in combination as suggested by Owsianiak et al. (2022). Such a combination of the two methods however implies considering contradicting assumptions in one single framework. We recall that EDP CFs are calculated considering that the *whole* emissions of a resource *i* to environment in the very long-term is equivalent to primary production at present. Instead, in their discussion of the ARP method, Owsianiak et al. (2022) state that "*not all emissions occurring in product life cycles are truly dissipative. This finding negates the default assumption that any elementary flow to the environment is dissipative […], and importantly should not be modeled as such in LCA*". Said in other words, following recommendations from the ARP method, not all emissions to environment shall be modelled as dissipative in the construction of the EDP CFs: EDP and ARP methods are inconsistent (ARP implements criterion A, while EDP does not) and shall not be used in combination.

iv) *Are all elements present in ores "expected to be accessible*"?

Criterion B is relevant by nature, enabling to get insights in understanding the differences in the quantities of mineral resources, versus non-resources, emitted to the environment. However implementation of criterion B is simplified through a number of assumptions, in particular assuming that "*any element present in any ore […] may also be considered accessible in the long term irrespective of its concentration level in that ore*". The authors support this assertion further assuming that "*reliable means of locating and extracting the ore are known and co-product elements can be reached with technological development if necessary in future*". This actually contradicts current capacities in the mining and metallurgical sector, in which efficiencies are below 100% regarding all elements in the input ores (Nassar et al., 2022). It assumes perfect efficiency through technological developments, which has not been observed in history so far. Here again, similarly to a number of other assumptions in $ADP_{ultimate\ reserves}$, EDP, and ARP itself, this other assumption in ARP does not reflect current knowledge, and is not the result of a predictive model; this is a techno-optimistic, probably uncertain, scenario.

6.3.4 JRC-LCI

6.3.4.1 Model, data and resulting inventorying approach

The JRC-LCI method consists in reporting, as "dissipative resource flow" at the unit process level, any flow of resources to i) environment; ii) final waste disposal facilities; and iii) products-in-use in the technosphere, with no full functionality (Chapter 3; Beylot et al., 2021). Dissipative flows may therefore be both elementary flows, from technosphere to ecosphere (as classically reported in LCIs) and flows within technosphere.

The implementation of the JRC-LCI method primarily builds on existing LCI data (e.g. in terms of emissions to environment), to be complemented in order to account for dissipative flows to certain compartments, in particular in the technosphere (not reported as dissipative flows in current standard LCI datasets). The data required for the "Resource flow analysis" (RFA, i.e. substance flow analysis of the resources; first step of the JRC-LCI method) are for some of them already reported directly in LCIs, or in documents supporting the description of LCI datasets. In the application to case studies, these data have been complemented with literature data and hypotheses required to make the LCI complete and consistent (Chapter 3 and Chapter 5; Beylot et al., 2021; Lai and Beylot, 2023).

6.3.4.2 Key assumptions, strengths and limits

6.3.4.2.1 Key assumptions

The JRC-LCI method relies on three main features and associated assumptions, which are discussed in the following.

i) Is the "short-term perspective" (25 years) applicable and relevant in contexts of products and systems with lifetimes longer than 25 years?

Beylot et al. (2021; Chapter 3) consider the definition of "dissipative flows" as suggested by Beylot et al.(2020b; Chapter 2): a resource is considered to be dissipated when it is rendered inaccessible to any future user; this "future" being set to 25 years in the JRC-LCI method. They recall that this is consistent

with common practice in LCA (e.g., in the PEF/OEF; Zampori and Pant, 2019), in which the exchanges with the ecosphere/technosphere along the life cycle of a product are integrated over the lifetime of the product under study. This makes the JRC-LCI method in this 25-year perspective also applicable and relevant in contexts of products and systems with lifetimes longer than 25 years.

ii) Are resource flows to final waste disposal facilities dissipated in a 25-year-perspective?

In the JRC-LCI method, resources in final disposal facilities are considered to be dissipated in the 25-year perspective. As of current state-of-play, the recovery of critical and other raw materials from extractive waste is not a widely diffused practice in the EU yet, despite there are some notable examples (Blengini et al., 2019). This makes this assumption in the JRC-LCI mostly, but still not entirely, valid.

More generally, the on/off classification (between dissipative and non-dissipative flows) may be further extended to better account for the severity of dissipation both between and within compartments, including in waste final disposal facilities. Dewulf et al. (2021) suggested an expert-based "duration of inaccessibility" with regard to resource flows as emitted into the environment, or derived to landfills, tailings final disposal facilities and dispersed into the technosphere by downcycling. Lai and Beylot (2023; Chapter 5) built on these durations of inaccessibility to complement the JRC-LCI method, and to account for the duration of inaccessibility of these resource flows once derived to dissipative compartments.

iii) Is occupation-in-use a form of dissipation?

None of the existing dissipation-based LCA methods, including the JRC-LCI method, capture reduced accessibility due to occupation-in-use of resources in the technosphere; i.e. within products of diverse lifetimes, from some years (e.g. smartphones) to some decades (e.g. up to 50 years in buildings). Beylot et al. (2021; Chapter 3) argue that occupation-in-use (also called "borrowing-in-use") is not considered as a dissipation because "*the function(s) that the resources could hold in the technosphere is (are) exploited"*. The JRC-LCI method focuses on dissipation, therefore excluding occupation-in-use; yet Beylot et al. (2021; Chapter 3) acknowledge that occupation-in-use could be additionally "*considered as potentially affecting the accessibility of the resources for other users*". As a potential future improvement of the JRC-LCI method, if deemed relevant, it may be extended to further account for accessibility of resources in other flows of the technosphere, in order to account for occupation-in-use in products.

6.3.4.2.2 Key strengths

The JRC-LCI method enables to account for the decrease in accessibility of mineral resources induced by product systems over their life cycle. The JRC-LCI method combined with price-based JRC CFs (see Chapter 4 and section below) enables to address the loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere; that is the damage to the safeguard subject for mineral resources as defined by the TF mineral resources of the Life Cycle Initiative (Berger et al., 2020).

The JRC-LCI method is based on a simple conceptual framework: in order to account for resource dissipation in LCA, dissipative resource flows shall be accounted for in LCIs, for each unit process step. The consideration of the short-term perspective is relevant for the developed resource indicator to

soundly support decision-making, e.g. in context of policy-making. This short-term perspective enables to define the list of dissipative flows based on today's knowledge and technological capacities for resource extraction and recovery, which are well-known and referenced. Accordingly the JRC-LCI method does not only consider dissipation to the environment, but instead dissipation in a larger sense; in particular in waste disposal facilities which represent potentially very significant sinks of dissipative flows.

Finally, the RFA at the basis of the JRC-LCI method enables improved quality of LCIs, in terms of completeness (more flows covered, including better coverage of emissions to environment) and consistency of resource flows over the life cycle of products and systems (coherent mass balances of resources, which is classically not the case in standard LCI datasets, e.g. in ecoinvent). It enables to distinguish mineral resource flows from non-mineral resource flows, accordingly enabling to flag those flows that are to be reported as dissipative resources.

6.3.4.2.3 Key limits

Yet the application of the JRC-LCI method has been so far limited to the foreground of the studied systems: dissipative flows need to be accounted for at each unit process of the analysed system, while LCI databases (e.g ecoinvent) used for background modelling do not report dissipative flows.

Moreover the improvement of LCI quality enabled by this method (improved completeness and consistency of LCI datasets) necessarily requires important efforts to compile balanced resource flows. Some of the data required to compute these mass balances are only available in reports supporting and describing the datasets (e.g. regarding waste final disposal facilities); or are simply disregarded. In addition to these efforts in new data compilation and recalculations, the JRC-LCI method requires a change in the nomenclature of flows classically compiled in LCI datasets, with the creation of new dissipative resource flows. The exact nomenclature for proper implementation in LCI datasets has so far been explored to a limited extent only.

Finally, despite relevant for support to policy-making, the short-term perspective of the JRC-LCI method may be not aligned with the temporal perspective considered in LCIA methods addressing other environmental challenges; e.g. regarding human toxicity and ecotoxicity for which longer temporal perspectives are usually considered.

6.3.5 JRC price-based

6.3.5.1 Model, data and resulting CFs

The JRC-LCIA method is based on the USGS Historical Statistics for Mineral and Material Commodities (Chapter 4). CF for a given resource is calculated as the ratio of its average price (in a certain timeframe) over the average price of a reference substance. A 50-year timeframe is considered, with timeframes of 10, 15, 20 and 30 years additionally considered for sensitivity analysis. CFs are in particular made available for 66 minerals and chemical elements based on their 50-year price-average, considering copper as the reference resource (Table 6.1). Alternative CFs are also available considering gold and antimony as reference substances.

6.3.5.2 Key strengths

When combined with the JRC-LCI method, or potentially other dissipation-based methods that capture the masses of resources dissipated, the JRC-LCIA method enables to address the loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere; that is the damage to the safeguard subject for mineral resources as defined by the TF mineral resources of the Life Cycle Initiative (Berger et al., 2020). CFs are fairly comprehensive, based on market price data which can be considered of good quality (in terms of completeness, precision and representativeness). The impact assessment method relies on a limited number of assumptions and layers of data whose uncertainty would add and propagate in the derivation of CFs. Despite only available in Excel format so far (Ardente et al., 2023), and not in classical LCA software, CFs have a high level of operability.

6.3.5.3 Key limits

Despite JRC price-based CFs are operational and have been tested on case studies, there is still as of today limited experience on their combination with the JRC-LCI method. In particular, the limit in operability of the latter, so far (as detailed in the above section), necessarily limits as well the use of these CFs to quantify value loss. Combination of price-based CFs with other more operational methods (at the LCI or impact assessment stages) is also possible (Table 6.1); yet to be further explored in particular in terms of consistency (e.g. of underlying assumptions in each method), operationalization (e.g. nomenclatures of mineral resources) and potential for support to decision-making.

Moreover, despite based on a limited number of assumptions, the price-based CFs rely on one core assumption: the market price of mineral resources would represent their value to humans.

Does the market price of mineral resources represent their value to humans?

On the production side, a number of parameters, including e.g. energy consumption and costs, appear to be factors in the determination of prices (Popp et al. 2018; Watson and Eggert, 2020), though with various degrees of correlation and rather complex mechanisms. On the demand side, the market price is however conditioned by the benefit that end-users will make from the use of these resources (i.e. by the value these resources hold for them). Using this indicator tends to protect resources with higher market prices: e.g. precious metals (gold, PGMs, silver) and specialty metals (rhenium, thallium, gallium, germanium, etc.) have CFs that are in general one to three orders of magnitude larger than that of copper (Chapter 4; Ardente et al., 2023). The JRC-LCIA method therefore protects the "exchange" (or "economic") value of resources, not their "use" (or "experiential") value to answer to human needs (here retaining definitions as in Charpentier-Poncelet et al., 2022a). It can be considered as a first proxy to quantify mineral resources value loss in LCA; yet with the need, in the more long-term, to refine this proxy with other metrics to better capture the actual "use" value of resources.

CFs are moreover based on prices for refined metals, despite some of these metals are dissipated upstream in the life cycle (i.e. in a non-refined form, at a stage in the life cycle where their concentration is potentially much lower). Using prices of refined metals accordingly implies overestimating the value loss associated with their dissipation. Conversely the value of metals in products-in-use, downstream the step of refining, may be larger than that of the refined metal; this shall also be explored further.

6.3.6 ADR and LPST

6.3.6.1 Model, data and resulting CFs

CFs published by Charpentier-Poncelet et al. (2021) for 18 metals are primarily based on dynamic Material Flow Analyses (MFAs) results. The data implemented in the dynamic MFA modelling in particular include: distribution of metals in 29 sectors of use, product lifetimes specific to each of these 29 applications, process yields, and collection and functional recycling rates; whose associated values are drawn from massive literature data collection. The extension of CFs to 61 metals is similarly based on extended and updated dynamic MFAs (Charpentier-Poncelet et al., 2022c).

The extension to the accounting of damages (endpoint ADR and LPST CFs) is based on average prices over 10 years, covering the period 2006-2015 in the majority of cases, building on USGS data. This essentially corresponds to data and sources similar to those of the JRC-LCIA CFs (in Chapter 4), considering however a different period to calculate average price values (50 year-average as the main period covered in the JRC method).

6.3.6.2 Key strengths

The midpoint ADR and LPST methods enable to account for the decrease in mineral resources accessibility, driven by resource dissipation, as induced by product systems over their life cycle. Moreover, as a complement, CFs are also available at endpoint to address the loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere; that is the damage to the safeguard subject for mineral resources as defined by the TF mineral resources of the Life Cycle Initiative (Berger et al., 2020). ADR and LPST CFs are based on massive, recent and overall reliable average data representative of mechanisms of mineral resource dissipation currently at stake in the technosphere. They can be used with current classical LCIs, including those of current databases (e.g. ecoinvent). They cover a fairly large range of chemical elements (61), despite not available yet for minerals (similarly to most other methods; Table 6.1).

6.3.6.3 Key limits

The ADR/LPST methods face three main limits in how far the associated CFs i) are compliant with LCIs, ii) build on the "true" service times of resources in the economy, and iii) can point to hotspot life cycle stages to support more resource-efficient solutions.

i) Are the parameters set to calculate the dynamic MFAs compliant with products/systems LCIs?

LPST and ADR CFs are based on a number of parameters in the underlying dynamic MFAs, whose associated values are set as fixed and representative of global use for each of the 61 resources covered. These parameters enable to quantify the average service times of resources. Some of these parameters may however be modelled differently in the LCI of the product systems under study; e.g. regarding production process yields, product lifetimes, recycling rates, etc. Depending on the LCA case studies at stake, part of these parameters will be modelled based on system-specific data, and/or on data from standard background databases. In both cases, it is very possible that the specific values in the LCI will deviate from the average values implemented in the computation of ADR and LPST CFs. Such potential inconsistencies between LCI and LCIA shall be further explored through case studies.

ii) How far LPST and ADR CFs build on the "true" service times of resources in the economy?

The values obtained from the MFA study correspond to a snapshot, based on recent data, representative of the current state-of-play, in particular regarding the following parameters: process yields, end-use applications, collection and end-of-life recycling rates. The distribution over time of dissipation of 1 kg of metal is calculated by following the fate from extraction towards total dissipation in the economy, representative of today's practices. For example regarding lithium: a 5% end-of-life recycling rate is considered for lithium ion batteries, whereas much larger values may be envisaged in future scenarios, as driven by developments in processes and policy incentives; see e.g. "conservative future" and "optimistic future" EoL disposal scenarios in Chapter 5 (Lai and Beylot, 2023) with recycling rates of respectively 40% and 80%. Similarly, scenarios for some key parameters in the dynamic MFA could be implemented based on more or less optimistic assumptions as compared to the current situation and state of knowledge. These scenarios would result in diverse ADR and LPST CFs. This may also be visible in any future update of the ADR and LPST methods.

iii) How supportive are ADR and LPST to solutions for improved resource use?

Finally, the ADR and LPST methods apply to resources extracted from ground, which on the one hand makes these methods particularly operational in the current context of classical LCI compilation, e.g. to perform contribution analysis for identification of hotspot economic exchanges and associated resources over the life cycle of a product system. But, on the other hand, ADR/LPST prevent any specific assessment regarding i) the life cycle stages mostly contributing to dissipation, and ii) dissipation compartments. These methods are particularly supportive to indicate a risk to use a resource that may dissipate faster than other resources, given the current state of its use, production processes, recycling practices, etc. at the global level.

6.4 Transversal analysis

Based on the above detailed analysis of each method, individually, we further perform a transversal, qualitative analysis. We consider the following criteria as key for possible implementation of these methods by LCA practitioners, and associated potential sound support to decision-making: i) relevance to the safeguard subject, ii) robustness of the model, iii) data quality and completeness, and iv) operability.

6.4.1 Relevance to the safeguard subject

The concept of "value loss" is core in the definition of the damage to the safeguard subject for mineral resources (Berger et al., 2020). This is despite there is still no commonly agreed understanding on the concept of "value" of mineral resources in the LCA community. Charpentier Poncelet et al. (2022a) in particular proposed to distinguish between the exchange (or economic) value and the use value (which for products refers to the experiential value that may be accredited to their functions). The combination of the JRC-LCI method with price-based JRC CFs enables to address the loss of exchange value induced by the use of mineral resources. One may similarly envisage to implement the JRC price-based CFs in combination with other methods that classify dissipative flows in LCI (e.g. ARP) in order to address the safeguard subject for mineral resources, despite this has not been done yet.

Moreover, the consideration of prices of resources as a complement to ADR and LPST CFs (Charpentier-Poncelet et al., 2022c) also enables to address the concept of exchange value loss. This makes the JRC-LCI combined with JRC price-based, the ADR and LPST endpoint methods, and potentially other

methods that classify dissipative flows in LCI (e.g. ARP), as relevant to address the safeguard subject for mineral resources. In parallel, the $ADP_{Ultimate\ Reserves}$ and EDP methods both do not address the loss of value of mineral resources explicitly. They instead address the concepts of contribution to respectively depletion and changed inaccessibility (in physical terms), as a result of resource extraction ($ADP_{Ultimate\ Reserves}$) or environmental dissipation (EDP; Figure 6.1).

6.4.2 Model robustness

The $ADP_{Ultimate\ Reserves}$, EDP and ARP methods rely on several assumptions at the same time core in the modelling of the impact pathway, and for some of them disputable (as discussed in the above sections 6.3.1 to 6.3.3). These assumptions are either common to some of these methods (e.g. reserve calculation based on continental crust content in $ADP_{Ultimate\ Reserves}$ and EDP); or specific to one method only (e.g. Criteria A and B in ARP method). The EDP and ARP methods are globally based on a larger number of assumptions compared to the $ADP_{Ultimate\ Reserves}$. In some cases these assumptions are contradictory in one single framework.

It is noteworthy that some proxies and assumptions are actually based on more or less optimistic or pessimistic scenarios. EDP and ARP build on techno-optimistic long-term scenarios, whereas the ADR/LPST methods consider the current situation as a representation for future practices; i.e. that on some aspects (in particular future recycling rates of some metals, e.g. those used in batteries) may be interpreted as a techno-pessimistic scenario. Moreover in the case of ADR/LPST methods, potential inconsistencies between LCI and LCIA shall be further explored through case studies.

Finally the JRC-LCIA method relies on a limited number of assumptions; still on one core, acceptable, assumption. The JRC-LCI moreover relies on assumptions supported by current knowledge on current practices; extended to future horizon in a reasonable perspective.

6.4.3 Data quality and completeness

Except the JRC-LCI method which requires specific data compilation at the foreground and background (in standard LCI databases) levels, all methods globally rely on data that are representative, complete and robust; that is, data of good to very good quality. Despite precision associated with these data is not quantified, reported and propagated to CFs (or in criteria regarding the ARP method), it may be qualified as high. Still the quantification of uncertainty in each parameter of CFs as well as its propagation to the resulting CFs shall be further explored.

It is however important to note that despite based on data of high precision, some of the methods are in the meantime based on potentially inaccurate assumptions and models (as discussed in the above section 6.4.2).

6.4.4 Operability

The analysed methods may globally be implemented by LCA practitioners with relative ease. This is in particular the case of the $ADP_{Ultimate\ Reserves}$ and ADR/LPST methods, whose CFs are available in standard LCA software (e.g. SimaPro) and that may be used with current approaches for mineral resources flows compilation in LCI (“extracted from ground”), as e.g. in ecoinvent or EF databases.

The main issue regarding operability relates to the JRC-LCI method, which requires significant effort of modifications of LCI datasets before it can be routinely operational (Chapter 5; Lai and Beylot, 2023). Similarly, the ARP method is not fully applicable in most LCA studies since, in order to classify an

emission to the environment as dissipative or not, one should know whether the metal that is emitted originates from a source where concentration is higher than average concentration in the upper crust ("Criterion B"). Such an information is so far absent from standard LCI databases. It is noteworthy that Owsianiak et al. (2022) applied the ARP method to four case studies, yet only in two cases out of the four in a complete version (i.e. with Criteria A *and* B).

6.5 Conclusions

This critical review chapter i) describes the characteristics of a selection of methods, and ii) discusses in-depth strengths and limits. It particularly highlights and challenges some of the key underlying choices and assumptions. Intentionally, this analysis does not eventually provide any recommendation on which methods shall be implemented. However, we encourage both the following:

- authoritative initiatives in the LCA domain (e.g. UNEP GLAM, PEF, etc.) to carefully consider this critical analysis also in view of future recommendations;
- LCA practitioners to cautiously consider the method they select, under the lens of this article.

Moreover, we additionally encourage to further improve some of the recently developed methods, with regard to some of their weak points; namely model robustness, ease of operation, or relevance for decision makers. In summary, two schools were identified in the way these methods intend to address the use of mineral resources in LCA, in terms of contribution to dissipation and reduced accessibility instead of contribution to depletion. A first one builds on the way elementary flows are currently reported in LCI databases (in particular, mineral resources as "extracted from ground"), trying to find ways to adapt by developing particular characterisation factors (ADR/LPST, EDP) or classification approaches for existing inventory flows (ARP). A second school advocates a more LCI driven approach and pledges for full blown, newly developed, LCIs (JRC-LCI method, as presented in Chapter 3).

7 Chapter 7 – Conclusions and perspectives

The major part of this Chapter 7 has been specifically developed in the context of this VAE. Moreover *Section 7.3 Conclusion on achievements and future perspectives* builds on the Conclusion section of:

Beylot, A., Dewulf, J., Greffe, T., Muller, S., Blengini, G.-A. 2023. Mineral resources depletion, dissipation and accessibility in LCA: a critical analysis. Submitted to the International Journal of Life Cycle Assessment.

Contribution of the co-authors and acknowledgements are reported previously in this document, as introduction to Chapter 6.

This document is a core, but not the only, piece of my application file for the validation of acquired experience to obtain the doctoral degree of the University of Bordeaux (in French "*Validation d'acquis de l'expérience, VAE, diplôme de doctorat*"). It reports the "*analysis of the work, methods and scientific results of one or more research*" that I carried out over my research career. It focuses on my contribution to the advancement of the LCA method through my research activities at the JRC of the EC and at the BRGM with a view to accounting for the dissipation of mineral resources and associated damage over the life cycle of products and systems.

This concluding Chapter 7 first discusses (in section 7.1) how the work presented from Chapter 2 to Chapter 6 enabled to answer the research objectives as initially set in Chapter 1. The following section 7.2 provides a final discussion on how this work advanced the LCA method to account for the dissipation of mineral resources and associated damage, firstly through a general overview and secondly through a discussion of the key strengths and limits in the developments. Finally section 7.3 further discusses some outcomes of the critical review reported in Chapter 6, opening to potential future perspectives and bridging with recent research initiatives I contributed to (Santillán-Saldivar et al., 2023; Dewulf et al., 2024)

7.1 Responses to the objectives

As stated in Chapter 1, as a core objective this research aimed at advancing the LCA method to account for the dissipation of mineral resources and associated damage over the life cycle of products and systems.

Chapter 2 enabled to complete SOa, i.e. *to conceptualize resource dissipation in the context of Life Cycle Thinking,* in particular *providing a unique definition for this concept out of its diverse understandings in literature*.

Chapter 3 presented the JRC-LCI method, that is a *method to capture mineral resource dissipation at the Life Cycle Inventory stage*, accordingly completing SOb.

Chapter 4 presented the price-based JRC-LCIA method, that is an *impact assessment method enabling to capture the damage induced by dissipative flows of mineral resources over the life cycle of products and systems*, accordingly completing SOc.

Chapter 5 tested the JRC-LCI method at the inventory level, by applying it to 11 case studies, both cradle-to-gate and considering a full life cycle perspective. It enabled to complete SOd, that is *to demonstrate the applicability of these methods and pave the way towards their implementation beyond the context of this research*. It moreover discussed about potential refinement of the price-based impact assessment method as developed in Chapter 4, in particular with capturing the duration of inaccessibility.

Finally Chapter 6 critically analysed recent resource-dissipation (or -accessibility) based methods, including the JRC-LCI and JRC-LCIA methods (as developed in Chapters 3 and 4), and methods developed by other researchers in the meantime. It similarly reviewed the ADP (depletion-based) method, which is the reference LCIA method in daily LCA practice. It enabled to complete SOe through discussing how *the new methods* described in Chapters 3 and 4 *have advanced the consideration of impacts associated with mineral resources use in LCA, including limits and potential for improvement in the future, in perspective with other key methods, long standing or on the contrary recently developed*.

7.2 Final discussion on the advancement of the LCA method to account for the dissipation of mineral resources and associated damage

7.2.1 General overview of the advancement of the LCA method

The concept of resource dissipation has gained increasing interest in the last two decades in life-cycle based studies. Chapter 2 shows that while most definitions in published studies intend to capture the difficulty/impossibility to recover a resource, there are different understandings of when a resource is actually difficult or impossible to be recovered and should accordingly be considered "dissipated". Chapter 2 accordingly provides i) a comprehensive definition for this concept, building from the literature review, and ii) a further discussion regarding its potential implementation in LCA considering today's existing datasets and best practices.

Chapter 3 subsequently builds on Chapter 2 to present a method (the JRC-LCI method) that enables to account for mineral resource dissipation along the life cycle of a product. Considering a short-term perspective (25 years), any flow of resources to i) environment, ii) final waste disposal facilities and iii) products-in-use in the technosphere (with low functionality) is suggested to be reported as dissipative at the level of unit processes. The JRC-LCI method accordingly enables to account for the decrease in accessibility of mineral resources induced by product systems over their life cycle. Chapter 4 moreover describes a price-based impact assessment method (JRC-LCIA) which quantifies the damage induced by the dissipative flows captured through the JRC-LCI method. The combination of the JRC method, at the LCI level (JRC-LCI, Chapter 3) and at the impact assessment level (JRC-LCIA, Chapter 4), eventually enables to address the loss of the potential to make use of the value that mineral resources can hold for humans in the technosphere; that is the damage to the safeguard subject for mineral resources as defined by the TF mineral resources of the UNEP Life Cycle Initiative (Berger et al., 2020).

Moreover Chapter 5 enables to test the JRC-LCI method at the inventory level, by applying it to 10 cradle-to-gate case studies (primary production of raw materials) as well as one case study considering the full life cycle of a mineral raw material–based product (lithium-ion battery for electric vehicles). The JRC-LCI method in particular enables to identify hotspots (in terms of life cycle steps) responsible for resource impacts all along the life cycle of a system (e.g., metallurgy and manufacturing processes, as well as EoL operations). The JRC-LCI method therefore provides a different perspective to the resource issue as classically considered in LCA, in which primary resource extraction is usually under focus (that is to say, considering mining operations as responsible for resource impacts).

Chapter 5 additionally discusses about potential refinement of the impact pathway as developed in Chapter 3 and Chapter 4. In Chapter 5, no specific temporal perspective is suggested to be defined for reporting "potentially dissipative" resource flows in the LCI step. Instead the temporal perspective is accounted for at the LCIA stage. Resources are accordingly considered to be inaccessible to future users, for a more or less long time span. The extent of this inaccessibility is expressed, and accounted for, as a duration over which the resources are inaccessible to future users, therefore enabling to account for the severity of dissipation.

Simultaneously to the development of the JRC-LCI and JRC-LCIA methods as presented in this work, other resource-dissipation (or -accessibility) based methods have been developed by other researchers in the meantime. Moreover, the ADP (depletion-based) method still remains the reference LCIA method in daily LCA practice. Chapter 6 describes the characteristics of these methods, and then performs an in-depth analysis including discussion on strengths and limits. It gives an overview of the methods' relevance to the safeguard subject, model robustness, data quality and completeness, and

operational capabilities. These aspects are discussed in the following section 7.2.2, with focus on the JRC-LCI and JRC-LCIA methods as developed in this work.

7.2.2 Key strengths and limits

Accounting for resource dissipation in LCIs – as is the core of the JRC-LCI method – implies partly transferring the resource focus from the extraction stage to stages later in the life cycle. That is to say, it implies accounting for resource dissipation through raw material production and manufacturing, use, recovery or final disposal. This method accordingly appears well adapted to better support more resource-efficient techniques or product designs. In particular, the JRC-LCI method enables LCA practitioners to identify potential improvements on life cycle stages for which the producer or user of the system under study has decisive influence. It may accordingly be particularly relevant to better support the development of more resource-efficient techniques or product designs.

Moreover the JRC-LCI method is based on a simple conceptual framework: in order to account for resource dissipation in LCA, dissipative resource flows shall be accounted for in LCIs, for each unit process step. The short-term perspective considered in this method is particularly relevant to soundly support decision-making, e.g. in context of policy-making. It enables to define the list of dissipative flows based on today's well-known and referenced technological capacities for resource extraction and recovery. Accordingly the JRC-LCI method does not only consider dissipation to the environment, but instead dissipation in a larger sense; in particular in waste disposal facilities which represent potentially very significant sinks of dissipative flows. Moreover, the RFA at the basis of the JRC-LCI method enables improved quality of LCIs, in terms of completeness and consistency of resource flows over the life cycle of products and systems. This RFA ensures coherent mass balances of resources, which is classically not the case in standard LCI datasets, e.g. in ecoinvent. It enables to distinguish mineral resource flows from non-mineral resource flows, accordingly enabling to flag those flows that are to be reported as dissipative resources.

However, at the current stage, the JRC-LCI method still faces limits in operability. The improvement of LCI quality enabled by this method (improved completeness and consistency of LCI datasets) necessarily requires important efforts to compile balanced resource flows. Some of the data required to compute these mass balances are only available in reports supporting and describing the datasets (e.g. regarding waste final disposal facilities); or are simply classically disregarded in current LCI databases. In addition to these efforts in new data compilation and recalculations, the JRC-LCI method requires a change in the nomenclature of flows classically compiled in LCI datasets, with the creation of new dissipative resource flows. The exact nomenclature for proper implementation in LCI datasets still needs to be further elaborated.

Modifications of LCI datasets are therefore necessary to eventually offer the possibility for LCA practitioners to use proper background data in their modelling, and accordingly to systematically account for abiotic resource dissipation in LCA based on the JRC-LCI method. This is expected to require relatively significant efforts, despite the application of the JRC-LCI method to 25 LCI datasets (over 10 case studies) in Chapter 5 showed its potential for replication, in particular thanks to a certain "snowball effect" in the implementation of RFA. Such potential requirement for large scale changes of LCI databases was identified early in this research, as reported in the conclusion section of Chapter 2 (referring to updating the existing datasets with new data related to dissipation only in a *long-term* perspective).

As discussed in Chapter 6, this limit in the operability of the JRC-LCI method may be put in perspective with, oppositely, the relative ease of implementation of some other methods. This in particular relates

to the $ADP_{Ultimate\ Reserves}$ and ADR/LPST methods, whose CFs are available in standard LCA software (e.g. SimaPro) and which may be used with current mineral resource flows as reported in standard LCI databases ("extracted from ground", as e.g. in ecoinvent or EF databases). The ADR/LPST, EDP, and ARP methods, developed simultaneously with my research work, found ways to adapt to current LCI datasets in order to address resource dissipation and/or reduced accessibility. They made a number of assumptions to develop operational characterisation factors (ADR/LPST, EDP) or classification approaches for existing inventory flows (ARP).

On another note, when potentially dissipative flows are reported in standard LCI databases, the duration of their inaccessibility (or, residence time) may be further considered, as suggested as an enhancement of the JRC-LCI method in Chapter 5. This accordingly enables to account for the severity of dissipation. However, as also acknowledged by Dewulf et al. (2021), the inaccessibility duration values are accompanied with a significant uncertainty which can be translated into very broad time spans. The actual durations of inaccessibility need to be further explored and refined in order to improve the reliability of the associated impact pathway.

Finally, the JRC-LCIA method builds on the price of resources, considered as a proxy for the multiple, complex and varied functions they can have for diverse economic sectors (electronics, automotive, aeronautics, etc.). However there is still no commonly agreed understanding on the concept of "value" of mineral resources in the LCA community. Charpentier Poncelet et al. (2022a) in particular proposed to distinguish between the *exchange* (or economic) value and the *use* value (which for products refers to the experiential value that may be accredited to their functions). The JRC-LCIA method captures the *exchange* value, and can be considered as a first proxy to quantify mineral resources value loss in LCA; yet with the need, in a longer term, to refine this proxy with other metrics to better capture the actual *use* value of resources.

7.3 Conclusion on achievements and future perspectives

In the critical analysis developed in Chapter 6, two schools were identified as to the way methods intend to address the use of mineral resources in LCA. A first one builds on the way mineral resources elementary flows have long been (and are still currently) reported in LCI databases (i.e., as "extracted from ground"). These developments have required ways to adapt by developing particular characterization factors (ADR/LPST, EDP) or classification approaches for existing inventory flows (ARP). The latter methods appear as intermediate solutions which can be applied with relative ease as of today by LCA practitioners, despite their development implied a number of assumptions and proxies as discussed in Chapter 6.

The JRC-LCI method was presented in Chapter 3, building on concepts developed in Chapter 2, and was further tested in Chapter 5. It is part of, and may be considered as among the initiators of, a second school that advocates a more LCI-driven approach and pledges for full blown, newly developed, LCIs. The inventory of mineral resources extracted from ground, as typically reported in LCIs (especially in LCI databases), was originally not intended to address losses of resources along the life cycle of the product system under study, but was rather intended to capture resource extraction at the very first stage of the life cycle. If the approach implemented by the "first school" may indeed provide operational methods in the short-term, it necessarily requires proxies to adapt to these unfit-for-purposes existing LCI datasets. The effort accordingly initiated by the "second school" calls for a change of paradigm on the way mineral resources are accounted for in LCA, with a view to not only building on primary resources extracted from ground but more generally capturing resource flows within technosphere and to ecosphere.

Interestingly the two schools may mutually take benefit of each other in future developments. For example, the ARP method ("first school") initiated a criterion-based approach to classify those emissions to environment that are indeed dissipative flows of mineral resources. Similarly a criterion-based approach could also be explored when developing new LCIs that capture dissipative flows not only to environment (as in the ARP method) but more generally to any compartment of dissipation, as in the JRC-LCI method ("second school").

More generally, improvement may require to explore new paths. Recalling that dissipative flows are inaccessible to future users (as per definition of Beylot et al., 2020b; Chapter 2), there still misses methods that enable to capture reduced accessibility not only due to inaccessible (dissipative) flows, but also more generally due to less accessible (yet, still accessible) flows as induced by compromising actions. This requires to go beyond:

1) the on/off character of approaches developed so far to capture dissipative flows at the LCI level; in particular through the JRC-LCI method. One may particularly cite the recently developed Economic Value Dissipation Potential (EVDP), a LCIA method that builds upon previous efforts presented in this document (JRC-LCI and JRC-LCIA methods as per Chapters 3 and 4) to address mineral resource dissipation in LCA (Santillán-Saldivar et al., 2023). It integrates two aspects in the evaluation of mineral resource dissipation in LCA: the identification of potentially dissipative flows, and the value loss associated to them.
2) the inability to capture increase of accessibility by e.g. exploration, mining and refining activities. In this regard, the recently developed Contribution To Inaccessibility-Life Cycle Impact Assessment (CTI-LCIA) method enables to point to hotspots along the life cycle (e.g. inaccessibility generation by storing in landfills and tailings deposits), the importance of process efficiencies, and the value of circular economy strategies (Dewulf et al., 2024). It builds on the RFA (i.e. substance flow analysis of the resources) as developed in the JRC-LCI method, mapping the flows of mineral resources into and out of the unit processes under study.

More generally, these improvements may gain insights from, and potentially be part of a more comprehensive development towards, the better accounting of impacts on resources in a large sense, not limited to mineral resources but also potentially extended to land and water (as e.g. initiated regarding water use by Pfister et al., 2016).

This change of paradigm on mineral resources in LCA, that this work contributed to initiate, will indeed require time and resources, in particular in terms of reconsidering the structure and content of current LCI databases. But it will be a necessary effort if the LCA community wants LCA to be truly supportive of sound decision-making towards more resource-efficient products and systems.

8 References

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Appendix A – Supporting information Chapter 2

A.1 Definitions for 'natural resources'

Table A1.1: Definitions for 'natural resources' (non-exhaustive list from the literature; Ardente et al., 2019)

Definition and reference
Natural resources can be defined as materials occurring in nature used and transformed by ecosystems and humans, as studied by ecology. (Odum et al., 1971)
Natural resources are natural assets (raw materials) occurring in nature that can be used for economic production or consumption. (UN, 1997)
A resource is an essential input to the economic process. Resources may be material or immaterial (e.g. information) and material resources may be of natural origin or man-made. Services provided by nature (e.g. `assimilative capacity') are also sometimes called resources. (Ayres, 2000)
Natural resources are objects of nature which are extracted by man from nature and taken as useful input to man-controlled processes, mostly economic processes. (Udo de Haes et al., 2002)
Natural resources include both the raw materials necessary for most human activities and the different environmental media, such as air, water and soil, which sustain life on our planet. (EC, 2003)
Resources are the backbone of every economy and provide two basic functions – raw materials for production of goods and services, and environmental services. (Mensah & Carmago Castro, 2004)
Natural resources pertains to materials that are extracted, harvested, or otherwise obtained from the environment for beneficial use by humans. (Bare and Gloria, 2006)
Natural resources can be defined as natural assets or endowments from which we derive value (utility). A broad definition would include environmental assets such as wilderness which, while they can be destroyed by human activity, do not have to be consumed in order to have value. (Hatcher, 2008)
Natural resources are stocks of materials that exist in the natural environment that are both scarce and economically useful in production or consumption, either in their raw state or after a minimal amount of processing. (WTO, 2010)
Natural resources provide essential inputs to production […]. Natural resources are also part of the ecosystems that support the provision of services such as climate regulation, flood control, natural habitats, amenities and cultural services that are necessary to develop man-made, human and social capital. (OECD, 2015)
Natural resources are the state's environmental and ecological assets; the land, water, plants and animals that sustain us and enhance our quality of life. (State of the Rhode Island, 2015)
Natural resources are defined broadly as the means for human actions and basis of human livelihoods provided by nature […]. They are extended by all ecosystem functions of earth and solar system usable by humans or funding human well-being […] and the extracted raw materials sub-categorised in biotic and abiotic materials. Their value for humanity as living resource-pools embedded in ecosystems or as single resource units is given by provisioning, supporting, cultural and regulating ecosystem - or resource-services. (Holzgreve, 2015)
Natural resources are any raw materials (matter or energy) which are not created by humans, but are available to sustain human activities. (Banai, 2016)
Natural resources are material and non-material assets occurring in nature that are at some point in time deemed useful for humans. (Sonderegger et al., 2017)
Resources — including land, water, air and materials — are seen as parts of the natural world that can be used in economic activities to produce goods and services. (IRP, 2019)

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A.2 Search string, short analysis of reviewed articles and list of references

A.2.1 Search string

In Chapter 2, the discussion is based on a literature search performed through Scopus, online database of peer-reviewed scientific publications in English. Two keywords were combined in the query, and screened within title, abstract and keywords: firstly, one keyword related to the concept of dissipation (either “dissipation” or “dissipative”), and secondly one keyword referring to the method implemented (either using their entire name or only their acronyms). The list of keywords used for the search is given below.

It is noteworthy that, as a complement, several articles and reports that have not been identified through this search process, but that we considered of particular relevance, have been additionally selected and reviewed. On the contrary, a first screening of this full set of references has enabled to exclude some articles, when the concept of dissipation was treated marginally.

Overall, the analysis is based on 45 publications reviewed (see section A.2.3 for the complete list of publications).

List of keywords used for the search:

"dissipation" and "Material Flow Analysis"
"dissipative" and "Material Flow Analysis"
"dissipation" and "MFA"
"dissipative" and "MFA"
"dissipation" and "Substance Flow Analysis"
"dissipative" and "Substance Flow Analysis"
"dissipation" and "SFA"
"dissipative" and "SFA"
"dissipation" and "Life Cycle Assessment"
"dissipative" and "Life Cycle Assessment"
"dissipation" and "LCA"
"dissipative" and "LCA"
"dissipation" and "Input-Output Analysis"
"dissipation" and "IOA" (or "IO" or "IO Analysis")
"dissipative" and "Input-Output Analysis"
"dissipative" and "IOA" (or "IO" or "IO Analysis")

A.2.2 Short analysis of reviewed articles

In most cases of publications reviewed, the information used to fill in the following table has been directly retrieved from the text. Yet, in some cases where the information in the publication was not fully explicit regarding some of the issues tackled in this table, the table was filled in also considering own interpretation of the publication. These cases are in particular reported with the terms "not fully explicit" in the cells.

Table A2.1: Short analysis of reviewed articles

Reference	Approach	Methodological developments / Case study	Scope of the case study	Lexical field used to refer to the concept of dissipation	Definition for "dissipation" (or related terms) explicitly provided	Compartments of occurence of dissipative flows: environment (emissions to), technosphere ("products in the technosphere") and waste disposal facilities	Explicit temporal perspective mentioned/applied to assess dissipation	Explicit parameters and thresholds mentioned/applied to assess dissipation
Rechberger and Graedel (2002)	SFA	Case study	Flows and stocks; Cu; Europe; early 1990s	Dissipation of copper; Copper used dissipatively	No	Environment	No	Yes. Relative Statistical Entropy as a parameter to assess the extent of dilution and dissipation along the Life Cycle of copper. But no threshold.
Rydh and Karlström (2002)	LCA	Case study	Environmental impact; recycling portable Ni-Cd batteries; Sweden	Dissipative losses	No	Environment	No	No
Spatari et al. (2002)	SFA	Case study	Flows and stocks; Cu; Europe; 1 year	Dissipative applications; Dissipative uses; Non-dissipative uses; Dissipative losses	No	Not explicit	No	No
Spatari et al. (2003)	SFA	Case study	Flows and stocks; Zn; selected western European countries; early 1990s	Dissipative uses; Dissipative flows; Dissipative losses; Dissipative cycles	No	Environment	No	No
Spatari et al. (2005)	SFA	Case study	Flows and stocks; Cu; North America; 20th century	Copper dissipated; Lost through dissipation; Materials dissipated	No	Environment	No	No
Stewart and Weidema (2005)	LCA	Method	General framework for assessing the impacts of (biotic and abiotic) resource use	Resource dissipation; dissipative use and disposal; resource dissipated or irreversibly fixed in composites; loss of resources; loss of functionality; impacts from resource use	Yes	Not fully explicit considering this nomenclature. Yet the following compartments can be inferred from the general framework: Environment Technosphere Waste disposal facilities	Yes, but without evaluation. Temporal aspects considered in the general framework (through the concept of backup technologies). They are also referred to by authors when defining the term "unavailable".	Yes. Parameters and thresholds are discussed by type of resources, but without valuation. The parameters discussed in particular include concentration and mineralogy regarding metallic minerals, and particle size regarding non-metallic minerals. Considering these parameters, the *"ultimate quality limit*" is discussed, in particular "*based on thermodynamic arguments*"

								in its general definition according to authors.
Johnson et al. (2006)	SFA	Case study	Flows and stocks; Cr; 54 countries, 9 world regions, planet; year 2000	Dissipation of Chromium; Dissipation flows; Losses; Dissipative uses	No	Environment Waste disposal facilities	No	No
Villalba et al. (2007)	SFA	Case study	Flows and stocks; F; global; year 2001	Substance dissipated; dissipative uses; dissipative losses	No	Environment	No	No
Tabayashi (2009)	SFA	Case study	Flows and stocks; Zn; Japan; year 2005	Dissipative use; Dissipative zinc	No	Environment	No	No
Guo et al. (2010)	SFA	Case study	Flows and stocks; Zn; China; year 2006	Dissipative losses	No	Not explicit	No	No
Arvidsson et al. (2011)	SFA	Case study	Flows (emissions); Ag nanoparticles; current at the time the article was published	Dissipative applications; Dissipative / non-dissipative use	No	Environment	No	No
Schneider et al. (2011)	LCA	Method	New characterisation factors for the impact category depletion of abiotic resources	Dissipated stock; Material dissipation	Yes	Environment	Yes. Yet mentioned in general terms.	No
Lifset et al. (2012)	SFA	Case study	Flows (to the environment); Cu; the United States; period 1975 to 2000	Dissipative uses and releases; Dissipative flows	Yes	Environment	Yes. Yet mentioned in general terms.	No
Ziemann et al. (2012)	SFA	Case study	Flows and stocks; Li; global; year 2007	Dissipative applications; Dissipative use; Dissipative losses	Yes	Environment	No	No
Zimmermann and Gößling-Reisemann (2013)	Specific approach	Case study	Screening of dissipative losses relative to critical materials	Dissipative losses; Dissipated metals	Yes	Environment Technosphere Waste disposal facilities	Yes. Regarding: - the dynamic nature of the assessment of dissipative losses ("*losses […] dissipative today might be less dissipative in the future*") - and the residence time as a qualitative parameter to differentiate dissipation types. Yet, not evaluated.	Yes, "small concentrations" of materials in a medium are mentioned as a parameter in the definition of dissipative losses. Yet, it is not used in the assessment (no valuation, no threshold implemented)

Johansson et al. (2013)	MFA	Method	Investigating the "technosphere mining" concept, including landfills, tailings, and slags mining.	Dissipated metal resources / material / stocks; Dissipation mining	Yes	Environment	No	No
Kral et al. (2013)	Specific approach	Method	Discussion paper on a "clean cycle" strategy	Dissipation of substances; Dissipative material releases; Dissipated materials; Dissipative losses; Dissipative material losses	Yes	Environment	No	No
Liang and Mao (2014)	SFA	Case study	Flows (to the environment); Pb; China; year 2010	Dissipative use; Dissipative lead; Loss from athropogenic lead flow	No	Environment Waste disposal facilities	No	No
Müller et al. (2014)	SFA	Method	Literature review of the methodologies applied in 60 dynamic MFAs of metals	Dissipative flows; Material dissipation; Metals dissipated	Yes	Environment Waste disposal facilities	No	No
Nakamura et al. (2014)	WIO-MFA	Case study	Flows and stocks; car steel recovered from End-of-Life vehicles ; over 100 years	Dissipation; losses (production, recovery and refinery losses)	No	Not explicit with respect to this nomenclature. Yet, distinguishing: - "production losses" (also termed "manufacturing losses") - "recovery losses of EoL products" - "refinery losses"	Yes, in a way. Dynamic modeling considering a 100 years, in particular with accounting for evolving rates of losses.	No
Stamp et al. (2014)	MFA	Case study	Primary metal (In) demand related to energy system transition scenarios	Dissipation; Material losses	Yes	Not explicit	Yes, issue mentioned regarding historic residues. But not considered (quantified) in the assessment.	No
Zimmermann and Gößling-Reisemann (2014)	Specific approach	Case study	Stocks and flows; selected critical metals; end-of-life of three different products	Materials / metals dissipate; Materials' dissipation; Material losses; Dissipative losses	No	Technosphere	No	Yes, (low) concentration mentioned but not used in the assessment.
Vadenbo et al., 2014	LCA	Method	Overview of presentations and discussions in a "discussion forum" on abiotic resources in LCA	Dissipative use of resources	No	Not explicit.	Yes, mentioned but not further discussed.	Yes, "(current) recovery costs" and "resource concentrations" mentioned as potential criteria to draw the boudary between borrowing and dissipative uses.

BIO by Deloitte (2015)	MSA	Case study	Stocks and flows + additional information (securiy of supply, substitutes, etc.) ; 28 case-study materials (including metals, aggregates, coking coal); EU; 2012	In use dissipation; Dissipative use; Metal is dissipated; Material losses; Material output from the value chain	Yes, regarding losses and in-use dissipation.	Losses: Environment Technosphere Dissipation: Environment	No	No
Ciacci et al. (2015)	Specific approach	Case study	Quantification of, and discussion on, "losses by design"; 56 metals and metalloids	Dissipative losses; Dissipative flows; Dissipative uses; Dissipative applications; Dissipation rate; Elements dissipated; Element / material losses	Yes	Environment Waste disposal facilities	Yes, mentioned in general terms but not evaluated.	Yes, "concentrations" and "technological and/or economic barriers" are mentioned in the description of concepts relative to "dissipation". But not quantitatively considered in the case study.
Duygan and Meylan, 2015	MFA	Case study	Stocks and flows; material flows of obsolete laptops and mobile phones + Cu, Ag, Au and Pd; Switzerland, 2011	Dissipative structure / composition; Dissipation of metals ; Substances, obsolete mobile phones, etc., lost	No	Technosphere	No	No
Ohno et al. (2015)	WIO-MFA	Case study	Assessment of environmental and economic benefits of alternative End-of-Life Vehicles (ELV) recycling schemes; focus on alloying elements in ELV-derived steel scrap	Alloying elements dissipated; Resource dissipation; Material / dilution losses; Loss of resource / alloying element	No	Not fully explicit considering this nomenclature. Yet the following compartments can be inferred: Technosphere Waste disposal facilities	No	No
Licht et al. (2015)	SFA	Case study	Stocks and flows; Ga, Ge, In; global; year 2011	Dissipative losses; Dissipative end uses; Metals (e.g. Ge) dissipated	No	Environment Technosphere Waste disposal facilities	No	Yes, but used only in a very limited extent. Concept of "small quantities" (and implicitely of small concentrations) considered to classify a flow as dissipative.
Paraskevas et al. (2015)	LCA	Case study	environmental impact of Al recycling; quantifying and accounting for material, dilution and quality losses	Dissipation; Losses; Material losses; Quality losses; Dilution losses	Yes, regarding the concept of "losses"	Not fully explicit considering this nomenclature. Yet the following compartments can be inferred with respect to what the authors refer to as "losses": Technosphere Waste disposal facilities	No	No

Schneider et al. (2015)	LCA	Method	estimation of the resource stocks ultimately available for human use in the long-term; application for the assessment of resource depletion in LCA	Dissipation of resources; anthropogenic stocks dissipation; inevitable loss of resources; loss of a material	No	Not explicit	Not explicitely regarding the concept of dissipation.	Yes, in a way. A default dissipation rate of 20% is considered.
Sonnemann et al. (2015)	LCA	Method	Discussion on integrating the criticality of resources into Life Cycle Sustainability Assessment	Resource dissipation; Resource is dissipated; Losses	Yes	Not explicit	Yes. Yet mentioned in general terms and in a very limited manner.	Not discussed
Drielsma et al. (2016)	LCA	Method	Presenting emerging consensus points that came out of a workshop on mineral resources in LCIA	Dissipative outflows (connected to the concept of resource availability)	No	Not explicit	Not discussed / considered regarding the concept of "dissipation", but mentioned regarding the concept of "resource availability"	No
Ciacci et al. (2016)	SFA and LCA	Case study	environmental impact (greenhouse gases); 50 metals; future efficiency improvements and saved primary production	Metal / material losses; Losses during use (in-use dissipation); Losses after use (constraints to metal recycling); Dissipative losses; Flows dissipated; Material dissipation	Yes, in a way, regarding losses.	Regarding losses: Environment Technosphere Waste disposal facilities	No	No
Takeyama et al. (2016)	WIO-MFA	Case study	Dissipation; Ni and Cr; steel materials in Japan; over 100 years	Alloy elements dissipated; Dissipation of Cr and Ni; Physical losses; Quality losses	Not explicitely, despite it is mentioned to be made of "physical losses" and "quality losses"	Not fully explicit considering this nomenclature. Yet it can be inferred that the following compartments are at least included: Technosphere Waste disposal facilities	No	No
van Oers and Guinée (2016)	LCA	Method	overview of problem definition and choices when defining the abiotic depletion potentials for use in LCIA; suggestions on possible new developments	Dissipative use of resources; loss of resources	No	Not explicit	No	No
Kovanda (2017)	MFA	Case study	Stocks and flows; total residual output flows; Czech Republic; 1990–2014	Dissipative flows; Dissipative use; Dissipative losses	Yes	Environment	No	No

Laner et al. (2017)	Statistical Entropy Analysis	Case study	Stocks and flows; P; Austria; different scenarios; 2000 and 2010	Dissipation of a substance; Substance dissipated; P losses; P lost	Not fully explicit. Yet, implicitely.	Environment Technosphere Waste disposal facilities	No	Yes. Statistical entropy as an indicator of dissipation. Comparison of input and output entropies, but no threshold.
Sonderegger et al. (2017)	LCA	Method	Natural resources as an Area of Protection in Life Cycle Impact Assessment; summary of discussion and findings of an expert group	Depletion / dissipation (of stock and fund resources) ; Natural resource / material is lost	Yes	Not explicit	No	Yes, partly explicited. A link is made between "dissipation", "concentrations below a threshold" and "loss". But not applied to any case study.
Zimmermann (2017)	SFA	Case study	Stocks and flows; different critical metals (In, Ga, Ge, Y); life cycle of selected products	Dissipative losses; Dissipation	Yes	Environment Technosphere Waste disposal facilities	Yes. The author mentions the "dynamic" nature of dissipative losses, linked to the technical or economic feasibility of recovering the material. Yet, not evaluated in the assessment (dissipative flows quantified considering the current feasibility of recovery).	Yes. Concentrations as a parameter mentioned in the definition. Also linked to the concept of technical and economical (un)feasibility of the material recovery. Yet, it is not used in the assessment (no evaluation, no threshold implemented)
Zampori and Sala (2017)	LCA	Method/simplified case study	General framework for assessing the impacts of abiotic resource dissipation	Dissipative use of resources; Dissipation; Dissipation to the technosphere; Dissipation within the environment	No	Environment Technosphere Waste disposal facilities	Yes, mentioned in general terms but not further discussed.	No
Krausmann et al. (2018)	MFA	Case study	Stocks and flows; materials; global economy; 1900–2015	Dissipative use	No	Not fully explicit considering this nomenclature.	Yes, in a way. Materials used in a dissipative way are reported to be typically consumed within a year after extraction. By opposition to materials which remain within the system for more than a year.	No. Classification of dissipative uses pre-defined by authors.
Nakamura and Kondo (2018)	WIO-MFA	Method	Description paper on a dynamic WIO model	Dissipation; Dissipated materials / metals; Dissipative applications	No	Technosphere Environment (specifically considering "dissipative applications", mentioned but excluded from the model)	Yes, in a way. The authors present their developments on a dynamic WIO model.	No

Nuss and Blengini (2018)	MFA	Method	Discussion on important interconnections between natural and anthropogenic cycles and relevant EU raw material dossiers	Metals / materials dissipated; Metals lost by dissipation; Dissipative losses	No	Not fully explicit considering this nomenclature.	Yes, mentioned in general terms, without evaluation.	No
Thiébaud et al. (2018)	SFA	Case study	Flows and stocks; In, Nd and Au; end-user devices in Switzerland	Metals are (irrecoverably) dissipated; Dissipation of metals; Dissipative flows; Losses through dissipation; Metal / resource losses	Yes, in part, with focus on the way dissipative flows are calculated	Environment Technosphere Waste disposal facilities Yet dissipation in Technosphere is only mentioned once in the introduction, whereas e.g. the Abstract clearly distinguishes Environment and Waste disposal facilities.	No	Yes, Statistical Entropy Analysis as a quantitative complement to the assessment of flows set as dissipative *"per se"*. But no threshold.
Tian et al. (2018)	IO-MFN	Case study	Flows (networks); Pb; China; 2012	Lead dissipated; Dissipation to the environment; Dissipate rates / level	No	Environment	No	No

A.2.3 List of references

Table A2.2: List of references

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Appendix B – Supporting information Chapter 3

This Appendix complements the description of the "resource flow analysis" in the case study (in Chapter 3), by providing details on:
- shares of resources in input and output flows;
- type of dissipation (e.g. dissipative use as a reagent);
- data used and assumptions.

The following sub-sections respectively refer to:
1) copper mining and concentration (using the ecoinvent dataset "copper mine operation, sulfide ore, GLO" as a support to the application of the approach described in Chapter 3)
2) copper production from the copper concentrate (using the ecoinvent dataset "copper production, primary, GLO")

B.1 Details on Resource Flow Analysis: mining and concentration of a sulfidic copper ore

Table B1: Mining and concentration of a sulfidic copper ore: resources in input and output flows, and details on the corresponding calculations

	Input flows		Output flows			Comments	
Resource (in EF nomenclature)	**Primary from ground**	**Embodied in products from technosphere**	**Product and by-product**	**Tailings**	**Environment**	**On transfer from input to output**	**On calculations: data used and assumptions**
Copper	98%	2%	82%	18%	0%	Copper is a resource targeted through the process; not 100% full conservation (in output product) due to process efficiency inferior to 100%. Also minor dissipation associated to dissipative use of reagents (use of copper sulphate as an activator)	- the flow to the environment corresponds to the mass of copper emitted to the environment (to air and water), as provided in the ecoinvent dataset. - the flow to tailings is calculated by mass balance: copper inputs (essentially in the ore) - copper dissipated to the environment - copper in the output product = copper in tailings
Molybdenum	100%	0%	29%	71%	0%	Molybdenum is a resource targeted through the process; not 100% full conservation (in output product) due to process efficiency inferior to 100%. Larger dissipation than in the case of copper because the main targeted resource is copper; molybdenum is only a by-product.	- the flow to the environment corresponds to the mass of molybdenum emitted to the environment (to air and water), as provided in the ecoinvent dataset (that is, 0: no emission considered in ecoinvent); - the flow to tailings is calculated by mass balance: molybdenum inputs (in the ore) - molybdenum dissipated to the environment (0) - molybdenum in the output product (molybdenite) = molybdenum in tailings
Zinc	0%	100%	0%	99.8%	0.2%	Dissipative use as a reagent of flotation (zinc sulphate)	Zinc is used dissipatively (as a depressant in the process). - the flow to the environment corresponds to the mass of zinc emitted to the environment as reported in the ecoinvent dataset; - the flow to tailings is calculated by difference between: zinc as a resource in the inputs - zinc dissipated to the environment

Sulfur	0%	100%	0%	50%	50%	Dissipative use as reagents of flotation (collector, depressant, activator). Moreover, similarly to what is done in the current ecoinvent database, in this study it is assumed that the sulfur in the ore is not a resource.	Sulfur is used dissipatively. The following assumption is considered: - 50% of sulfur is derived to the environment (to water) - and 50% in tailings.
Sodium	0%	100%	0%	100%	0%	Dissipative use as a reagent (one element of sodium cyanide)	Sodium is used dissipatively. - No emission of Sodium to the environment is reported in the ecoinvent dataset. - Sodium in the input is considered to be entirely derived to the tailings
Potassium	0%	100%	0%	100%	0%	Dissipative use as a reagent (potassium ethyl xanthate as the collector considered)	Potassium is used dissipatively. - No emission of Potassium to the environment is reported in the ecoinvent dataset. - Potassium in the input is considered to be entirely derived to the tailings
Calcium carbonate	0%	100%	0%	0%	100%	Dissipative use as a reagent (packed lime)	Using the ecoinvent dataset (packed lime used in input) and assuming full dissipation to the environment through reaction
Nickel	0%	100%	0%	99.9%	0.1%	Dissipative use through milling (abrasion of steel)	Emissions to the environment as in the ecoinvent dataset. Remaining share in tailings calculated by use of the mass in input (in steel)
Chromium	0%	100%	0%	99.97%	0.03%	Dissipative use through milling (abrasion of steel)	
Iron	0%	100%	0%	99.9%	0.1%	Dissipative use through milling (abrasion of steel)	

B.2 Details on Resource Flow Analysis: Copper from copper concentrate

Table B2: Copper from copper concentrate: resources in input and output flows, and details on the corresponding calculations

	Input flows		Output flows			Comments	
Resource (in EF nomenclature)	**Primary from ground**	**Embodied in products from technosphere**	**Product**	**Slags**	**Environment**	**On transfer from input to output**	**On calculations: data used and assumptions**
Copper	0%	100%	96.8%	2.9%	0.3%	Resource targeted through the process; not 100% full conservation (in output product) due to process efficiency inferior to 100%.	- the flow to the environment corresponds to the mass of copper emitted to the environment (to air and water), as provided in the ecoinvent dataset; - the flow to slags is calculated by mass balance: copper inputs (in the concentrate) - copper dissipated to the environment - copper in the output product = copper in slags
Carbon	0%	100%	0%	100%	0%	Graphite used as an electrode. In the absence of specifications, assumed to be derived into slags as a proxy.	This input resource to the process does not appear in the output products; it is assumed to be entirely derived to the slags.
Calcium carbonate	0%	100%	0%	0%	100%	Dissipative use as a reagent.	Using the ecoinvent dataset (packed lime used in input) and assuming full emission to the environment through reaction
Quartz sand	0%	100%	0%	100%	0%	Use as a reagent: silica sand to cause iron in the copper concentrate to accumulate in the slag phase, while copper accumulates in the matte phase.	Quartz sand is considered to be transferred entirely to the slags.

Appendix C – Supporting information Chapter 4

C.1 Characterization Factors, with Cu as reference substance

Elaboration based on values from: https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

Table C1: Price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value: Characterization Factors, with Cu as reference substance

Characterization factors [kg $Cu_{€\ eq}$/kg]	Average 10 years	Average 15 years	Average 20 years	Average 30 years	Average 50 years
Bauxite	3.91E-03	4.76E-03	5.70E-03	7.29E-03	1.03E-02
Barite	1.39E-02	1.50E-02	1.62E-02	1.72E-02	1.69E-02
As	9.06E-02	1.34E-01	1.78E-01	2.33E-01	2.64E-01
Sb	1.17E+00	1.15E+00	1.11E+00	1.10E+00	1.38E+00
Al	3.26E-01	3.88E-01	4.40E-01	5.10E-01	5.65E-01
Be	5.71E+01	6.40E+01	1.14E+02	1.54E+02	1.45E+02
Bi	3.00E+00	3.03E+00	3.16E+00	3.27E+00	5.41E+00
B	1.10E-01	1.55E-01	1.92E-01	2.28E-01	2.27E-01
Br					3.15E-01
Cd	4.77E-01	4.93E-01	4.98E-01	1.08E+00	2.62E+00
Cr	3.33E-01	3.53E-01	3.63E-01	3.67E-01	3.17E-01
Clays	6.44E-03	6.93E-03	7.45E-03	8.02E-03	7.11E-03
Co	5.39E+00	6.41E+00	8.41E+00	9.32E+00	9.32E+00
Cu	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Diatomite	3.72E-02	4.99E-02	5.97E-02	7.05E-02	6.89E-02
Feldspar	1.23E-02	1.47E-02	1.64E-02	1.69E-02	1.59E-02
Fluorspar					6.04E-02
Ga	7.03E+01	9.59E+01	1.21E+02	1.40E+02	3.54E+02
Garnet	4.07E-02	5.23E-02	6.21E-02	7.48E-02	8.92E-02
Ge	1.94E+02	2.06E+02	2.84E+02	3.35E+02	3.13E+02
Au	5.10E+03	5.06E+03	5.06E+03	5.14E+03	4.46E+03
N. Graphite	1.31E-01	1.43E-01	1.62E-01	1.78E-01	1.36E-01
Gypsum	2.25E-03	2.93E-03	3.34E-03	3.89E-03	7.13E-03
Hf	6.14E+01	6.64E+01	6.99E+01	7.44E+01	1.00E+02
In	8.32E+01	9.62E+01	1.03E+02	1.02E+02	1.08E+02
I	4.16E+00	4.42E+00	4.83E+00	4.97E+00	4.42E+00
Fe and steel		1.37E-01	1.42E-01	1.53E-01	1.64E-01
Kyanite	4.24E-02	4.98E-02	5.76E-02	5.85E-02	6.12E-02
Pb	3.29E-01	3.50E-01	3.70E-01	3.60E-01	3.58E-01
Lime	1.49E-02	1.71E-02	1.88E-02	2.03E-02	2.06E-02
Li	5.67E-01	5.81E-01	8.03E-01	1.05E+00	1.14E+00

Mn	2.00E-01	2.14E-01	2.25E-01	2.30E-01	1.87E-01
Mg	6.87E-01	7.68E-01	8.94E-01	1.06E+00	1.10E+00
Hg	5.06E+00	4.77E+00	4.45E+00	4.02E+00	5.57E+00
Mo	5.30E+00	6.20E+00	5.85E+00	5.09E+00	5.59E+00
Ni	2.88E+00	3.10E+00	3.13E+00	3.21E+00	2.99E+00
Nb					4.69E+00
N	6.89E-02	7.49E-02	7.60E-02	7.03E-02	7.80E-02
Perlite	7.19E-03	8.70E-03	9.72E-03	1.08E-02	1.19E-02
P rock	1.11E-02	1.13E-02	1.15E-02	1.08E-02	1.01E-02
PGM	2.80E+03	3.33E+03	3.62E+03	3.90E+03	3.56E+03
K	7.88E-02	7.86E-02	7.84E-02	7.41E-02	6.31E-02
Pumice	4.17E-03	5.08E-03	6.00E-03	6.74E-03	5.37E-03
Quartz					7.21E+01
REE	2.86E+00	2.87E+00	2.98E+00	2.96E+00	2.27E+00
Re	6.16E+02	5.87E+02	5.62E+02	5.20E+02	7.06E+02
Salt	5.63E-03	6.62E-03	7.37E-03	7.96E-03	7.89E-03
Sand & Gravel	1.05E-03	1.25E-03	1.39E-03	1.47E-03	1.41E-03
Se	1.10E+01	1.18E+01	1.07E+01	9.26E+00	1.22E+01
Ag	8.91E+01	8.68E+01	8.61E+01	8.21E+01	9.30E+01
Si	3.15E-01	3.55E-01	4.01E-01	4.24E-01	4.37E-01
Stone	2.69E-02	3.58E-02	4.42E-02	5.40E-02	5.63E-02
Sr	1.31E-01	1.68E-01	1.99E-01	2.10E-01	1.68E-01
S	1.28E-02	1.23E-02	1.28E-02	1.76E-02	2.41E-02
Talc	2.43E-02	2.78E-02	3.14E-02	3.57E-02	3.56E-02
Ta	2.76E+01	2.91E+01	3.75E+01	3.65E+01	3.88E+01
Te	2.19E+01	2.23E+01	2.20E+01	2.30E+01	2.00E+01
Tl	8.35E+02	7.99E+02	7.75E+02	6.18E+02	3.55E+02
Ti	1.73E+00	2.15E+00	2.49E+00	2.95E+00	3.50E+00
Sn	3.18E+00	3.26E+00	3.38E+00	3.50E+00	4.50E+00
W	5.48E+00	5.56E+00	5.39E+00	4.89E+00	5.89E+00
Va	3.84E+00	4.65E+00	4.89E+00	5.10E+00	5.81E+00
Vermiculite					3.66E-02
Wollastonite	2.69E-02	3.34E-02	3.89E-02	4.43E-02	4.71E-02
Zn	3.37E-01	3.55E-01	3.89E-01	4.27E-01	4.28E-01
Zr	1.72E-01	1.74E-01	1.77E-01	1.63E-01	1.30E-01

C.2 Characterization Factors, with Sb as reference substance

Elaboration based on values from: https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

Table C2: Price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value: Characterization Factors, with Sb as reference substance

Characterization factors [kg $Sb_{€\ eq}$/kg]	Average 10 years	Average 15 years	Average 20 years	Average 30 years	Average 50 years
Bauxite	3.33E-03	4.15E-03	5.12E-03	6.62E-03	7.47E-03
Barite	1.19E-02	1.31E-02	1.46E-02	1.57E-02	1.23E-02
As	7.72E-02	1.17E-01	1.60E-01	2.11E-01	1.92E-01
Sb	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Al	2.78E-01	3.38E-01	3.95E-01	4.64E-01	4.11E-01
Be	4.86E+01	5.58E+01	1.02E+02	1.40E+02	1.06E+02
Bi	2.56E+00	2.64E+00	2.83E+00	2.97E+00	3.93E+00
B	9.36E-02	1.35E-01	1.73E-01	2.07E-01	1.65E-01
Br					2.29E-01
Cd	4.07E-01	4.29E-01	4.47E-01	9.81E-01	1.90E+00
Cr	2.84E-01	3.08E-01	3.26E-01	3.33E-01	2.31E-01
Clays	5.49E-03	6.04E-03	6.69E-03	7.29E-03	5.17E-03
Co	4.60E+00	5.58E+00	7.54E+00	8.47E+00	6.78E+00
Cu	8.52E-01	8.71E-01	8.97E-01	9.08E-01	7.27E-01
Diatomite	3.17E-02	4.35E-02	5.36E-02	6.40E-02	5.01E-02
Feldspar	1.05E-02	1.28E-02	1.48E-02	1.53E-02	1.16E-02
Fluorspar	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.39E-02
Ga	5.99E+01	8.36E+01	1.08E+02	1.27E+02	2.57E+02
Garnet	3.47E-02	4.56E-02	5.58E-02	6.80E-02	6.49E-02
Ge	1.65E+02	1.79E+02	2.55E+02	3.05E+02	2.28E+02
Au	4.35E+03	4.41E+03	4.54E+03	4.67E+03	3.24E+03
N. Graphite	1.12E-01	1.25E-01	1.45E-01	1.62E-01	9.91E-02
Gypsum	1.92E-03	2.55E-03	3.00E-03	3.53E-03	5.19E-03
Hf	5.24E+01	5.78E+01	6.27E+01	6.76E+01	7.29E+01
In	7.09E+01	8.38E+01	9.28E+01	9.24E+01	7.82E+01
I	3.54E+00	3.85E+00	4.33E+00	4.52E+00	3.21E+00
Fe and steel	1.13E-01	1.19E-01	1.27E-01	1.39E-01	1.19E-01
Kyanite	3.61E-02	4.34E-02	5.17E-02	5.32E-02	4.45E-02
Pb	2.80E-01	3.05E-01	3.32E-01	3.27E-01	2.61E-01
Lime	1.27E-02	1.49E-02	1.69E-02	1.85E-02	1.50E-02
Li	4.83E-01	5.07E-01	7.21E-01	9.55E-01	8.30E-01
Mn	1.70E-01	1.86E-01	2.02E-01	2.09E-01	1.36E-01
Mg	5.86E-01	6.69E-01	8.02E-01	9.64E-01	8.01E-01
Hg	4.31E+00	4.16E+00	3.99E+00	3.65E+00	4.05E+00
Mo	4.51E+00	5.41E+00	5.25E+00	4.62E+00	4.06E+00

Ni	2.45E+00	2.70E+00	2.81E+00	2.91E+00	2.18E+00
Nb					3.41E+00
N	5.87E-02	6.53E-02	6.82E-02	6.38E-02	5.67E-02
Perlite	6.13E-03	7.58E-03	8.72E-03	9.79E-03	8.64E-03
P rock	9.50E-03	9.84E-03	1.03E-02	9.78E-03	7.31E-03
PGM	2.39E+03	2.90E+03	3.25E+03	3.54E+03	2.59E+03
K	6.71E-02	6.85E-02	7.03E-02	6.73E-02	4.59E-02
Pumice	3.55E-03	4.42E-03	5.39E-03	6.12E-03	3.90E-03
Quartz					5.24E+01
REE	2.44E+00	2.50E+00	2.68E+00	2.69E+00	1.65E+00
Re	5.25E+02	5.11E+02	5.05E+02	4.72E+02	5.14E+02
Salt	4.80E-03	5.77E-03	6.62E-03	7.23E-03	5.73E-03
Sand & Gravel	8.98E-04	1.09E-03	1.25E-03	1.33E-03	1.03E-03
Se	9.35E+00	1.03E+01	9.57E+00	8.41E+00	8.87E+00
Ag	7.59E+01	7.56E+01	7.73E+01	7.45E+01	6.76E+01
Si	2.68E-01	3.09E-01	3.60E-01	3.85E-01	3.18E-01
Stone	2.29E-02	3.12E-02	3.97E-02	4.91E-02	4.09E-02
Sr	1.11E-01	1.46E-01	1.78E-01	1.90E-01	1.22E-01
S	1.09E-02	1.07E-02	1.15E-02	1.60E-02	1.75E-02
Talc	2.07E-02	2.42E-02	2.82E-02	3.24E-02	2.59E-02
Ta	2.35E+01	2.54E+01	3.37E+01	3.31E+01	2.82E+01
Te	1.87E+01	1.95E+01	1.97E+01	2.09E+01	1.45E+01
Tl	7.12E+02	6.96E+02	6.95E+02	5.61E+02	2.58E+02
Ti	1.47E+00	1.87E+00	2.24E+00	2.68E+00	2.54E+00
Sn	2.71E+00	2.84E+00	3.03E+00	3.18E+00	3.27E+00
W	4.67E+00	4.84E+00	4.83E+00	4.45E+00	4.28E+00
Va	3.27E+00	4.05E+00	4.39E+00	4.64E+00	4.22E+00
Vermiculite					2.66E-02
Wollastonite	2.29E-02	2.91E-02	3.49E-02	4.02E-02	3.43E-02
Zn	2.87E-01	3.10E-01	3.49E-01	3.88E-01	3.11E-01
Zr	1.46E-01	1.52E-01	1.59E-01	1.48E-01	9.46E-02

C.3 Characterization Factors, with Au as reference substance

Elaboration based on values from: https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

Table C3: Price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value: Characterization Factors, with Au as reference substance

Characterization factors [kg $Au_{€\ eq}$/kg]	Average 10 years	Average 15 years	Average 20 years	Average 30 years	Average 50 years
Bauxite	7.66E-07	9.41E-07	1.13E-06	1.42E-06	2.30E-06
Barite	2.73E-06	2.96E-06	3.21E-06	3.36E-06	3.80E-06
As	1.77E-05	2.65E-05	3.52E-05	4.53E-05	5.92E-05
Sb	2.30E-04	2.27E-04	2.20E-04	2.14E-04	3.08E-04
Al	6.39E-05	7.66E-05	8.71E-05	9.93E-05	1.27E-04
Be	1.12E-02	1.27E-02	2.25E-02	2.99E-02	3.26E-02
Bi	5.88E-04	5.98E-04	6.25E-04	6.36E-04	1.21E-03
B	2.15E-05	3.05E-05	3.80E-05	4.43E-05	5.09E-05
Br					7.08E-05
Cd	9.35E-05	9.74E-05	9.85E-05	2.10E-04	5.87E-04
Cr	6.53E-05	6.97E-05	7.19E-05	7.14E-05	7.12E-05
Clays	1.26E-06	1.37E-06	1.47E-06	1.56E-06	1.60E-06
Co	1.06E-03	1.27E-03	1.66E-03	1.81E-03	2.09E-03
Cu	1.96E-04	1.98E-04	1.98E-04	1.95E-04	2.24E-04
Diatomite	7.29E-06	9.86E-06	1.18E-05	1.37E-05	1.55E-05
Feldspar	2.41E-06	2.90E-06	3.25E-06	3.29E-06	3.57E-06
Fluorspar	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E-05
Ga	1.38E-02	1.90E-02	2.39E-02	2.72E-02	7.94E-02
Garnet	7.98E-06	1.03E-05	1.23E-05	1.46E-05	2.00E-05
Ge	3.80E-02	4.07E-02	5.62E-02	6.52E-02	7.02E-02
Au	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
N. Graphite	2.57E-05	2.83E-05	3.20E-05	3.47E-05	3.06E-05
Gypsum	4.41E-07	5.79E-07	6.61E-07	7.56E-07	1.60E-06
Hf	1.20E-02	1.31E-02	1.38E-02	1.45E-02	2.25E-02
In	1.63E-02	1.90E-02	2.05E-02	1.98E-02	2.41E-02
I	8.15E-04	8.73E-04	9.55E-04	9.67E-04	9.91E-04
Fe and steel	2.61E-05	2.70E-05	2.80E-05	2.98E-05	3.68E-05
Kyanite	8.30E-06	9.83E-06	1.14E-05	1.14E-05	1.37E-05
Pb	6.44E-05	6.92E-05	7.32E-05	7.01E-05	8.04E-05
Lime	2.92E-06	3.37E-06	3.72E-06	3.96E-06	4.62E-06
Li	1.11E-04	1.15E-04	1.59E-04	2.05E-04	2.56E-04
Mn	3.91E-05	4.22E-05	4.45E-05	4.48E-05	4.20E-05
Mg	1.35E-04	1.52E-04	1.77E-04	2.07E-04	2.47E-04
Hg	9.91E-04	9.43E-04	8.81E-04	7.82E-04	1.25E-03

Mo	1.04E-03	1.23E-03	1.16E-03	9.91E-04	1.25E-03
Ni	5.64E-04	6.13E-04	6.20E-04	6.24E-04	6.71E-04
Nb					1.05E-03
N	1.35E-05	1.48E-05	1.50E-05	1.37E-05	1.75E-05
Perlite	1.41E-06	1.72E-06	1.92E-06	2.10E-06	2.67E-06
P rock	2.18E-06	2.23E-06	2.27E-06	2.10E-06	2.25E-06
PGM	5.49E-01	6.58E-01	7.16E-01	7.59E-01	7.99E-01
K	1.54E-05	1.55E-05	1.55E-05	1.44E-05	1.42E-05
Pumice	8.16E-07	1.00E-06	1.19E-06	1.31E-06	1.20E-06
Quartz					1.62E-02
REE	5.60E-04	5.67E-04	5.90E-04	5.75E-04	5.08E-04
Re	1.21E-01	1.16E-01	1.11E-01	1.01E-01	1.58E-01
Salt	1.10E-06	1.31E-06	1.46E-06	1.55E-06	1.77E-06
Sand & Gravel	2.06E-07	2.46E-07	2.74E-07	2.85E-07	3.17E-07
Se	2.15E-03	2.34E-03	2.11E-03	1.80E-03	2.73E-03
Ag	1.75E-02	1.71E-02	1.70E-02	1.60E-02	2.09E-02
Si	6.17E-05	7.01E-05	7.93E-05	8.25E-05	9.80E-05
Stone	5.27E-06	7.07E-06	8.75E-06	1.05E-05	1.26E-05
Sr	2.56E-05	3.31E-05	3.93E-05	4.08E-05	3.78E-05
S	2.51E-06	2.42E-06	2.53E-06	3.43E-06	5.41E-06
Talc	4.76E-06	5.49E-06	6.22E-06	6.94E-06	7.98E-06
Ta	5.40E-03	5.76E-03	7.42E-03	7.09E-03	8.71E-03
Te	4.29E-03	4.41E-03	4.35E-03	4.48E-03	4.49E-03
Tl	1.64E-01	1.58E-01	1.53E-01	1.20E-01	7.97E-02
Ti	3.38E-04	4.25E-04	4.93E-04	5.74E-04	7.85E-04
Sn	6.23E-04	6.44E-04	6.68E-04	6.82E-04	1.01E-03
W	1.07E-03	1.10E-03	1.07E-03	9.52E-04	1.32E-03
Va	7.53E-04	9.19E-04	9.67E-04	9.93E-04	1.30E-03
Vermiculite					8.22E-06
Wollastonite	5.28E-06	6.59E-06	7.69E-06	8.62E-06	1.06E-05
Zn	6.60E-05	7.02E-05	7.69E-05	8.31E-05	9.59E-05
Zr	3.36E-05	3.44E-05	3.51E-05	3.18E-05	2.92E-05

Appendix D – Supporting information Chapter 5

D.1 Characterization factors

The following table provides the endpoint characterization factors calculated by integrating the inaccessibility (reflected through durations) and value (reflected through market prices) of resources. Market prices are drawn from Ardente et al. (2023; Chapter 4) with considering 50 years averages and antimony as reference substance. These CFs are resource and compartment-specific. This enables reflecting a more or less long duration of inaccessibility of a given resource, as a function of the compartment of potential dissipation (final waste disposal facilities, environment or products-in-use).

Table D1: Characterization factors calculated by integrating the inaccessibility (reflected through durations) and value (reflected through market prices) of resources

Mineral resource	CFs - Final waste disposal facilities ($years_{Sb\ €eq}$)	CFs - Environment/Products-in-use ($years_{Sb\ €eq}$)
Bauxite	4.86E-01	3.73E+00
Barite	8.00E-01	6.16E+00
Arsenic (As)	1.25E+01	9.60E+01
Antimony (Sb)	6.50E+01	5.00E+02
Aluminum (Al)	2.67E+01	2.05E+02
Beryllium (Be)	6.87E+03	5.28E+04
Bismuth (Bi)	2.56E+02	1.97E+03
Boron (B)	1.07E+01	8.24E+01
Bromine (Br)	1.49E+01	1.15E+02
Cadmium (Cd)	1.24E+02	9.51E+02
Cement	1.05E+00	8.11E+00
Cesium (Cs)	3.08E+05	2.37E+06
Chromium (Cr)	1.50E+01	1.15E+02
Clays	3.36E-01	2.59E+00
Cobalt (Co)	4.41E+02	3.39E+03
Copper (Cu)	4.73E+01	3.64E+02
Industrial diamond	3.31E+05	2.55E+06
Diatomite	3.26E+00	2.50E+01
Feldspar	7.52E-01	5.79E+00
Fluorspar	2.86E+00	2.20E+01
Gallium (Ga)	1.67E+04	1.29E+05
Garnet	4.22E+00	3.24E+01
Germanium (Ge)	1.48E+04	1.14E+05
Gold (Au)	2.11E+05	1.62E+06
Natural graphite	6.44E+00	4.95E+01
Gypsum	3.37E-01	2.59E+00
Hafnium (Hf)	4.74E+03	3.65E+04
Helium (He)	2.06E+02	1.58E+03

Indium (In)	5.08E+03	3.91E+04
Iodine (I)	2.09E+02	1.61E+03
Steel	7.76E+00	5.97E+01
Iron (Fe) ore	6.40E-01	4.93E+00
Kyanite	2.89E+00	2.22E+01
Lead (Pb)	1.69E+01	1.30E+02
Lime	9.74E-01	7.49E+00
Lithium (Li)	5.39E+01	4.15E+02
Manganese (Mn)	8.84E+00	6.80E+01
Magnesium compounds	5.66E+00	4.36E+01
Magnesium (Mg)	5.21E+01	4.01E+02
Mercury (Hg)	2.63E+02	2.02E+03
Molybdenum (Mo)	2.64E+02	2.03E+03
Nickel (Ni)	1.41E+02	1.09E+03
Niobium (Nb)	2.22E+02	1.71E+03
Nitrogen (N)	3.69E+00	2.84E+01
Perlite	5.62E-01	4.32E+00
Phosphate (P) rock	4.75E-01	3.65E+00
Platinum group metal (PGM)	1.68E+05	1.29E+06
Potassium (K)	2.98E+00	2.30E+01
Pumice	2.54E-01	1.95E+00
Quartz	3.41E+03	2.62E+04
Rare earth element (REE)	1.07E+02	8.24E+02
Rhenium (Re)	3.34E+04	2.57E+05
Salt	3.73E-01	2.87E+00
Sand & gravel	6.68E-02	5.14E-01
Sand & gravel (industrial)	2.63E-01	2.02E+00
Selenium (Se)	5.76E+02	4.43E+03
Silver (Ag)	4.40E+03	3.38E+04
Silicon (Si)	2.06E+01	1.59E+02
Soda ash	1.40E+00	1.08E+01
Stone (crushed)	6.68E-02	5.14E-01
Stone	2.66E+00	2.05E+01
Strontium (Sr)	7.96E+00	6.12E+01
Sulfur (S)	1.14E+00	8.77E+00
Talc	1.68E+00	1.29E+01
Sodium sulphate	1.49E+00	1.15E+01
Tantalum (Ta)	1.83E+03	1.41E+04
Tellurium (Te)	9.46E+02	7.27E+03
Thallium (Tl)	1.68E+04	1.29E+05
Thorium (Th)	1.02E+03	7.88E+03
Titanium (Ti)	1.65E+02	1.27E+03
Titanium dioxide	2.65E+01	2.04E+02

Tin (Sn)	2.13E+02	1.64E+03
Tungsten (W)	2.78E+02	2.14E+03
Vanadium (V)	2.75E+02	2.11E+03
Vermiculite	1.73E+00	1.33E+01
Wollastonite	2.23E+00	1.71E+01
Zinc (Zn)	2.02E+01	1.56E+02
Zirconium (Zr)	6.15E+00	4.73E+01

D.2 Implementation of Resource Flow Analysis as first step of the JRC-LCI method: the case of nickel cradle-to-gate production

The following tables provide a detailed overview of the mineral resource flows identified through the implementation of RFA considering nickel "cradle-to-gate" production. For each unit process as modelled in the ecoinvent v3.7 database, the balance of input and output resource flows is detailed and accompanied with comments regarding each flow and information on the data (source, assumptions, and calculations) implemented in the RFA.

Table D.1: Ni cradle-to-gate production: resource flows and details regarding the data considered in the RFA for each unit process as modelled in the ecoinvent v3.7 database

	Input flows of mineral resources		Output flows of mineral resources				Comments	
Resource *(In EF nomenclature)*	**From ground**	**Embodied in products from technosphere**	**In output products** *(significant function)*	**In output products** *(low function)*	**In waste**	**To environment**	**On transfer from input to output**	**On the data and assumptions considered**
	Unit process: Nickel mine operation and benefication to nickel concentrate, 7% Ni							
Nickel (Ni)	100.0%	0.0%	86.8%	0.0%	12.5%	0.7%	Nickel is the main resource targeted through the process, here extracted from ground and transformed into nickel concentrate. Due to a process efficiency inferior to 100%, a share of the resource is conserved in the output product; while we consider the rest partly emitted to the environment (air) and partly derived to final waste disposal (as sulfidic tailings).	Resource inputs: - The nickel extracted from ground corresponds to the mass of nickel in ground, as reported in the ecoinvent inventory. Output (including dissipative) flows: - The nickel content in the concentrate is drawn from the ecoinvent dataset. - The flow to the environment (air) corresponds to the mass of nickel emitted to air, as reported in the ecoinvent inventory. - Considering ecoinvent data regarding Ni input as extracted from ground and Ni output as concentrate, emissions to air and sulfidic tailings, the Ni mass balance is not fulfilled. In this study, the ecoinvent data for Ni input from ground and output as concentrate and emissions are conserved; while the Ni output as sulfidic tailings is calculated by difference: *nickel extracted from ground - (nickel in concentrate + nickel emitted to air)*.
	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	Nickel also enters the unit process as infrastructure/equipment (mine infrastructure), considered to be derived to final waste disposal (as infrastructure waste) at end-of-life (EoL).	Resource inputs: - The nickel embodied in the infrastructure/equipment is derived from the ecoinvent inventories associated with the infrastructure/equipment, completed with information drawn from ecoinvent reports (Kellenberger et al., 2007; Classen et al., 2009). Output (including dissipative) flows: - No infrastructure/equipment waste is reported in the ecoinvent inventory. We consider that the total mass of nickel embodied in the infrastructure/equipment ends up in a waste that is disposed of (no recycling).

Aluminium (Al)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	Aluminium enters the unit process as infrastructure/equipment (mine infrastructure), considered to be derived to final waste disposal (as infrastructure waste) at end-of-life (EoL).	<u>Resource inputs:</u> - The aluminium embodied in the infrastructure/equipment is derived from the ecoinvent inventories associated with the infrastructure/equipment, completed with information drawn from ecoinvent reports (Kellenberger et al., 2007; Classen et al., 2009). <u>Output (including dissipative) flows:</u> - No infrastructure/equipment waste is reported in the ecoinvent inventory. We consider that the total mass of aluminium embodied in the infrastructure/equipment ends up in a waste that is disposed of (no recycling).
Bauxite	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Clay	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Calcium carbonate ($CaCO_3$)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Calcium (Ca)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Sand	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Gypsum	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Quartz sand (SiO_2)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Gravel	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Magnesium (Mg)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Iron (Fe)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Manganese (Mn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Phosphorus (P)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Chromium (Cr)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Sulfur (S)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Potassium (K)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Sodium (Na)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Molybdenum (Mo)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Niobium (Nb)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al

Tungsten (W)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Vanadium (V)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Basalt	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Dolomite	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Zinc (Zn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Copper (Cu)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Tin (Sn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
	Unit process: Smelting and refining of nickel concentrate, 7% Ni (with application of economic allocation)							
Nickel (Ni)	0.0%	100.0%	92.9%	0.2%	6.9%	0.0%	Nickel is the main resource targeted through the process, here transformed from nickel concentrate to nickel class 1. Due to a process efficiency inferior to 100%, a share of the resource is conserved in the output product; while we consider the rest partly recovered in products-in-use with a low-functionality (as cement, incorporating nickel smelter slag), partly derived to final waste disposal (as nickel smelter slag) and partly emitted to the environment (air).	<u>Resource inputs:</u> - The nickel content in the concentrate is drawn from the ecoinvent dataset. <u>Output (including dissipative) flows:</u> - The nickel content in nickel class 1 is drawn from the ecoinvent dataset. - The flow to the environment (air) corresponds to the mass of nickel emitted to air, as reported in the ecoinvent inventory. - Considering ecoinvent data regarding Ni input as concentrate and Ni output as nickel class 1, emissions to air and smelter slag, the Ni mass balance is not fulfilled. In this study, the ecoinvent data for Ni input and output as nickel class 1 and emissions are conserved; while the Ni output as smelter slag is calculated by difference: *nickel in concentrate - (nickel in nickel class 1 + nickel emitted to air).* Moreover, we consider that a share of the nickel smelter slag is incorporated in cement, while the rest is derived to final waste disposal, based on ecoinvent data.
	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	Nickel also enters the unit process as infrastructure/equipment (aluminium hydroxide factory, non-ferrous smelter), considered to be derived to final waste disposal (as infrastructure waste) at end-of-life (EoL).	<u>Resource inputs:</u> - The nickel embodied in the infrastructure/equipment is derived from the ecoinvent inventories associated with the infrastructure/equipment, completed with information drawn from ecoinvent reports (Kellenberger et al., 2007; Classen et al., 2009). <u>Output (including dissipative) flows:</u> - No infrastructure/equipment waste is reported in the ecoinvent inventory. We consider that the total mass of nickel embodied

								in the infrastructure/equipment ends up in a waste that is disposed of (no recycling).
Sulfur (S)	0.0%	100.0%	93.9%	0.0%	0.0%	6.1%	Sulfur enters the unit process as reagent/ancillary material (sulfuric acid), considered to be partly conserved in an output product (as ammonium sulfate) and partly emitted to the environment (air) through the process.	Resource inputs: - Considering the ecoinvent data regarding S input as sulfuric acid and calculated data regarding S outputs as ammonium sulfate and emissions to air, the S mass balance is not fulfilled. In this study, the data for S outputs are conserved; while the S input as sulfuric acid is set equal to the S outputs: *sulfur in ammonium sulfate + sulfur emitted to air*. Output (including dissipative) flows: - The flow to the environment (air) is calculated by stoichiometry, based on the mass of sulfur dioxide reported in the ecoinvent inventory and its chemical formula. - The sulfur content in the ammonium sulfate is calculated by stoichiometry, based on its chemical formula.
Chlorine (Cl)	0.0%	100.0%	0.0%	2.4%	97.6%	0.0%	Chlorine enters the unit process as reagent/ancillary material (liquid chlorine and hydrochloric acid), considered to be partly recovered in products-in-use with a low-functionality (cement, incorporating nickel smelter slag) and partly derived to final waste disposal (as nickel smelter slag) through the process.	Resource inputs: - The liquid chlorine input corresponds to the mass of liquid chlorine input, as reported in the ecoinvent inventory. - The chlorine content in the hydrochloric acid is calculated by stoichiometry, based on its chemical formula. Output (including dissipative) flows: - No emission of chlorine is reported in the ecoinvent inventory. We consider that the total mass of chlorine inputs ends up in nickel smelter slag. Moreover, we consider that a share of the nickel smelter slag is incorporated in cement, while the rest is derived to final waste disposal, based on ecoinvent data.

Aluminium (Al)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	Aluminium enters the unit process as infrastructure/equipment (aluminium hydroxide factory, non-ferrous smelter), considered to be derived to final waste disposal (as infrastructure waste) at end-of-life (EoL).	<u>Resource inputs:</u> - The aluminium embodied in the infrastructure/equipment is derived from the ecoinvent inventories associated with the infrastructure/equipment, completed with information drawn from ecoinvent reports (Kellenberger et al., 2007; Classen et al., 2009). <u>Output (including dissipative) flows:</u> - No infrastructure/equipment waste is reported in the ecoinvent inventory. We consider that the total mass of aluminium embodied in the infrastructure/equipment ends up in a waste that is disposed of (no recycling).
Bauxite	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Clay	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Calcium carbonate ($CaCO_3$)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Calcium (Ca)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Sand	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Gypsum	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Quartz sand (SiO_2)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Gravel	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Magnesium (Mg)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Iron (Fe)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Manganese (Mn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Phosphorus (P)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Chromium (Cr)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Potassium (K)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Sodium (Na)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Molybdenum (Mo)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Niobium (Nb)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Tungsten (W)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al

Vanadium (V)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Basalt	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Dolomite	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Zinc (Zn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Copper (Cu)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al
Tin (Sn)	0.0%	100.0%	0.0%	0.0%	100.0%	0.0%	cf. Al	cf. Al

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Appendix E – Supporting information Chapter 6

This Appendix describes the methods reviewed, in terms of: concept, target, resource flows in scope, midpoint and/or endpoint impact mechanism, and temporal scope.

1. ADP ultimate reserves

The Abiotic Depletion Potential method, ultimate reserves ($ADP_{ultimate\ reserves}$), is intended to capture the issue of mineral resource depletion; i.e. the contribution to exhaust the stock of a non-renewable resource, in turn limiting its availability to future generations. It was originally published by Guinée (1995), with updates in 2002 (van Oers et al., 2002) and 2020 (van Oers et al., 2020a). Extraction of mineral resources from ground is considered to contribute to the depletion/exhaustion of the primary stock (i.e., stock in the environment): "reserve", "reserve base", "resources" or "ultimate reserves", with a temporal timeframe from short to very long. In the latest recommendations by the UN (Berger et al, 2020), "stock" is set to *ultimate reserves*, which corresponds to the $ADP_{ultimate\ reserves}$ method. It adopts an infinite timeframe and builds on the ultimate reserve, a hypothetical upper limit of the amount of resources that may be extracted from common rock, with the average composition of earth crust, assuming that future technologies will make it possible to extract it (Sonderegger et al., 2020). ADP CFs apply to resource flows "extracted from ground" by the mining sector, as typically compiled in standard LCI databases (e.g. ecoinvent or Environmental Footprint – EF - databases).

2. EDP

The project SUPRIM developed both a conceptual framework to develop characterization factors to address mineral resource use in LCA, and an operational method. The conceptual framework is intended to capture the decreased accessibility of mineral resources due to the net result of compromising actions, that is stated to be the problem induced by current resource use for future generations (van Oers et al., 2020b). Four compromising actions are distinguished: i) exploration, ii) dissipation to environment, iii) hibernation in technosphere (corresponding to unused stocks in technosphere, in the absence of economic drivers in the time horizon considered) and iv) occupation-in-use. The SUPRIM conceptual framework has so far been operationalized for a very long-term perspective only. In order to make this conceptual framework operational, the authors make the following assumptions and choices:

- continental crustal content is used as a proxy for the accessible stock in the environment and technosphere (similarly to the approach undertaken in the ADP method);
- hibernation in use is considered to be negligible, due to economic and technological developments that will make the hibernating stocks accessible over the very long term;
- occupation in use is also considered to be negligible;
- and finally, exploration is irrelevant in the very long-term, as "*its maximum possible contribution is already included in the chosen proxy for the total accessible stock*" (van Oers et al., 2020b);

The authors claim that these assumptions correspond to a scenario that "*will happen at some point in the far future*" (van Oers et al., 2020b), with explicitly excluding any precise timeframe for the

completion of this scenario (e.g. 100 years, 1000 years, or even more). Eventually only environmental dissipation is considered as relevant in this context. In the resulting Environmental Dissipation Potential (EDP) method, all emissions to environment are considered dissipative flows. EDP CFs aim at accounting for the severity of this dissipation.

3. ARP

The ARP (Abiotic Resources Project) method (Owsianiak et al., 2022) is intended to capture the decrease of accessibility of mineral resources. The method enables to classify an emission of a metal to the environment as dissipative, or not, in product life cycles at the LCI stage of LCA. It aims at improving the former consideration of environmental dissipation in the EDP operationalized method, in which all emissions to environment are considered dissipative (Owsianiak et al., 2022). The ARP method instead intends to distinguish "*truly dissipative*" emissions from those that do not contribute to loss of accessibility of a given resource. This firstly requires the identification of emissions of resources, by opposition to emissions of non-resources. Emissions may indeed originate from a source of the element that would not be considered as a mineral resource now, or in the future within the timeframe considered ("*e.g., emission of a metal though combustion of fossil coal, where it is present in trace amounts in the coal and is not expected to be considered as a metal resource*"; Owsianiak et al., 2022); therefore not contributing to mineral resource dissipation, as also advocated by Beylot et al. (2021; Chapter 3).

Secondly the ARP method considers that part of the emissions to the environment may at some point (now or in a more or less long future) be accessible to some users, accordingly not contributing to resource dissipation. The implementation of the method is based on dissipation criteria developed specifically for a very long-term (infinite) timeframe. In addition, as an example of application to case studies, it is combined with EDP CFs, with associated CFs made available to users.

4. JRC-LCI

The JRC-LCI method (Chapter 3) applies at the LCI step. It builds on the definition of *resource dissipation* derived by Beylot et al. (2020b; Chapter 2) from their literature review of life-cycle-based studies. The JRC-LCI method consists in reporting dissipative flows of mineral resources at the unit process level, in mass units (Beylot et al., 2021), considering a predefined list of dissipative mineral resource flows to a number of dissipation (receiving) compartments. The dissipative nature of flows, and of dissipation compartments, depends on the temporal perspective. A short-term perspective (25 years) is suggested to be considered, as it is particularly adapted to support decision-making, and especially in contexts of policy-making. Any flow of resources to i) environment; ii) final waste disposal facilities (landfills and tailings final disposal facilities); and iii) products-in-use in the technosphere, in which the resource no longer provides any significant function (including due to low-functional recycling), is suggested to be reported as dissipative at the unit process level. This approach enables to capture four of the six actions compromising the accessibility to mineral resources, as defined by Dewulf et al. (2021): emitting, landfilling, tailing, downcycling/dispersing into the technosphere. "Resource flow analysis" (RFA, i.e. substance flow analysis of the resources) is at the core of the JRC-LCI method. LCA practitioners shall firstly map the flows of mineral resources into and out of the unit processes under study, then list the dissipative flows, and finally report them in the LCI at the unit process level.

Despite suggested to be implemented considering a short-term perspective, the JRC-LCI method is based on a framework that may be alternatively implemented considering different temporal perspectives. Beylot et al. (2021; Chapter 3) accordingly test the JRC-LCI framework considering a long-term perspective, assuming that in the long-run only emissions of resources to environment are dissipative. In that case (long-term perspective), the "dissipative flows" in the JRC-LCI "long-term" method would become conceptually:

1. close to the dissipative flows considered in the EDP method, however: i) recalling that the EDP method provides characterization factors which apply to these dissipative flows, and ii) considering only *resources* emitted to environment as dissipative flows in the JRC-LCI "long-term" method (while all emissions to environment, including of non-resources, are considered dissipative resource flows in the EDP method) ;
2. and close to the dissipative flows in the ARP method, yet without considering any criterion to assess the future accessibility or inaccessibility of resources emitted to environment (contrarily to the ARP method).

This distinction between "JRC-LCI framework" (applicable for any temporal perspective) and "JRC-LCI method" (for a given temporal perspective) made, it is noteworthy that in Chapter 6 the terms "JRC-LCI method" refer to the method that builds on a short-term perspective. This is in line with the suggestion of the JRC-LCI method developers (Beylot et al., 2021; Chapter 3).

5. JRC price-based

The JRC price-based method is an impact assessment method which builds on the price of resources, considered as a proxy for the multiple, complex and varied functions they can have for diverse economic sectors (electronics, automotive, aeronautics, etc.; Ardente et al., 2023; Chapter 4). CF for a given resource is calculated as the ratio of its average price (in a certain timeframe) over the average price of a reference substance. It is neither based on the depletion nor on the dissipation approaches, but rather on the user value that the current and past generations attribute to metals and minerals, which also reflects market expectation for the coming years (forward looking short time frame).

These CFs are primarily intended to be used in combination with dissipation-based methods at the LCI step; that is, they are applicable to dissipative resource flows compiled in LCIs. The rationale is that dissipative flows (or losses) of mineral resources are by definition not accessible anymore to humans in a given temporal perspective. This subsequently implies the loss of the value these resources can hold for humans in the technosphere. JRC price-based CFs have been tested so far in combination with the JRC-LCI method. All the flows of different mineral resources dissipated in the inventory phase are translated in an equivalent mass of a reference resource based on their relative values (Ardente et al., 2023; Chapter 4). Said in other words, price-based CFs combined with the JRC-LCI method enable to quantify the mineral resource Value Loss along the life cycle of the system under study, expressed e.g. in kg Cu.€eq in case copper is chosen as the reference substance.

Potential for application in combination with other dissipation methods (e.g. the ARP method that classifies dissipative flows at the LCI step) could be further tested as well. Price-based CFs (or underlying price data) are additionally potentially applicable both i) directly with classical LCI datasets that account for resources extracted from ground, and ii) as potential complements to existing LCIA methods not capturing damage to resource value (as done e.g. in the case of the ADR and LPST methods extended to endpoint impact modelling; see in the following).

6. ADR and LPST

According to Charpentier Poncelet et al. (2022c), the Average Dissipation Rate (ADR) and Lost Potential Service Time (LPST) methods are intended to quantify respectively *"the relative contribution of a product system to the dissipation of mineral resources"*, and "*the relative contribution of a product system to the inaccessibility of mineral resources due to dissipation*". ADR and LPST CFs apply at the impact assessment step in combination with classical approaches for mineral resources elementary flows accounting at the LCI step ("extracted from ground"), as in current standard LCI databases (e.g. ecoinvent or EF).

Both the ADR and LPST methods build on the service time (ST) of resources, that is the duration over which resources provide a service within the economy, from their extraction from ecosphere until dissipation after one or several uses. The definition and scope of dissipation is identical to that developed by Beylot et al. (2021; Chapter 3). In particular compartments of dissipation are essentially similar to those considered in the JRC-LCI method: final waste disposal facilities, emissions to environment and non-functionally recycled resources. ST is calculated as a function of product lifetimes and dissipation over the resources life cycle. Dissipation primarily depends on process yields, dissipative uses, and collection and functional recycling rates.

The ADR method corresponds to a rate, by definition, which is the inverse of the total ST. This rate is a snapshot value depicting current status on dissipation and resources lifetimes in the economy, considering current performances in processes (including, recycling) and lifetimes of products extrapolated from now to a long-term horizon. It does not include any prospective scenario on future trends regarding resource applications in the economy and process (including recycling) performances. It was calculated by Charpentier Poncelet et al. (2021, 2022b) through dynamic Material Flow Analyses (MFAs), initially for 18 chemical elements and further updated for 61 elements. Moreover, LPST is a "distance-to-target" concept that is based on the difference between current situation on ST, for each resource, and a hypothetical absence of dissipation over a given temporal horizon (i.e. 100 or 500 years of optimal service time respectively over 100 and 500 years).

Charpentier Poncelet et al. (2022c) additionally suggest an extension from midpoint ADR and LPST CFs to endpoint CFs, intended to *"quantify the relative contribution of a product system to the potential mineral resource value lost due to dissipation*". Extension from midpoint to endpoint is based on price indices (ratio of the price of one metal over the price of a reference metal), conceptually very similar to the price-based CFs of the JRC price-based impact assessment method. The major difference relies on the way these CFs are applied: respectively directly on dissipative resource flows as reported in LCIs (JRC price-based CFs combined with JRC-LCI method; in Chapter 4), or in combination with midpoint ADR and LPST CFs which apply to resources extracted from ground in LCIs (in Charpentier Poncelet et al., 2022c).

SCIENTIFIC PRODUCTION

This Chapter stands for Part 3 of my application file for the validation of acquired experience to obtain the doctoral degree of the University of Bordeaux (in French "*Validation d'acquis de l'expérience, VAE, diplôme de doctorat*"). It first reports, and classifies by research object, the international publications in peer-reviewed journals and the book chapters that I contributed to. It is followed by the list of my communications in international congresses with or without publication of proceedings, compiled together with my contribution to scientific and technical reports.

Regarding the international publications in peer-reviewed journals, it is noteworthy that I have contributed to 35 publications in total since the start of my research career. This includes 19 publications as first author, and 7 publications as second author. The first publications I contributed to were released in 2013, i.e. 10 years ago.

International publications in peer-reviewed journals, classified by research topic

Impact on the Area of Protection natural resources in LCA: new methods to better support decision-making

Beylot, A., Ardente, F., Sala, S., Zampori, L., 2021. Mineral resource dissipation in life cycle inventories. The International Journal of Life Cycle Assessment 26, 497–510. https://doi.org/10.1007/s11367-021-01875-4

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Santillán-Saldivar, J., **Beylot, A.**, Cor, E., Monnier, E., Muller, S., 2023. Economic value dissipation potential (EVDP): an improved method to estimate the potential economic value loss due to resource dissipation in life cycle assessment. The International Journal of Life Cycle Assessment 28, 1400–1418. https://doi.org/10.1007/s11367-023-02204-7

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Oral presentations in international congresses

In the following I report some of the oral presentations I performed in the past years, with focus on the main and most recent ones.

Huppertz, T., **Beylot, A.**, Decaevel, B. Innovative methods for resources use in LCA. 2023. The 11th Conference on Life Cycle Management. LCM2023. 6th-8th September 2023, Lille, France.

Santillán-Saldivar, J., **Beylot, A.**, Muller, S., Cor, E., Monnier, E. 2023. Estimation of potential economic value losses due to resource dissipation in LCA through the EVDP method. A case on LIB recycling. SETAC Europe 33rd Annual Meeting. Dublin, Ireland.

Beylot, A., Muller, S., Lai, F., Villeneuve, J. 2022. From resource depletion to resource dissipation in LCA: overview of recent methodological developments. 16th Society and Materials Conference (SAM16). 8th-9th November 2022.

Beylot, A., Muller, S., Guezennec, A.-G., Bodénan, F., 2022. LCA of tailings management: current status, potentials and challenges. Re-Mine Symposium, 17th May 2022. Mechelen, Belgium

Beylot, A. 2021. LCA of metals production: key challenges ahead and potential way forward. PROMETIA Life Cycle Analysis Webinar. 31st August 2021. https://prometia.eu/2021/09/21/prometia-held-a-webinar-on-lca-and-sustainability-on-31-august/

Beylot, A., Corrado, S., Sala, S. 2019. Environmental impacts of EU-consumption: comparing process-based LCA and Input-Output analysis towards supporting SDG 12 on sustainable production and consumption. 1-4 September, 2019. Poznan University of Technology. Poznan, Poland

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