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Critical materials and dissipative losses: A screening study

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HIGHLIGHTS

- The presented work analyses dissipative losses of critical materials according to the EU definition.
- A classification scheme for dissipative losses considering stage of occurrence and receiving medium is presented.
- A screening showed that for all assessed critical materials dissipative losses occur in a rather significant scale.
- Assessing dissipation is a data intensive endeavor. Detailed MFAs are required here.
- Based on a prioritization of dissipative losses, optimization measures can be developed.

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ABSTRACT

This study deals with dissipative losses of critical materials between the life-cycle stages of manufacturing and end-of-life. Following the EU definition for critical materials, a screening of dissipative losses for the respective materials has been performed based on existing data and the most significant data gaps have been identified. Furthermore, a classification scheme for dissipative losses (dissipation into environment, dissipation into other material flows, dissipation to landfills) and for assessing their degree has been developed and a first qualitative assessment applying this classification scheme has been performed.

In combination with existing criticality assessments, the results can be used to generate a map of metals indicating future research needs for analyzing metal dissipation in detail. The results include quantitative estimates of dissipative losses (where feasible) along the chosen life-cycle stages, and discuss research needs for analysis and avoidance of dissipative losses for improved resource efficiency.

1. Introduction

The criticality of materials is a field of research of increasing attention. There are various studies on criticality available (e.g. Erdmann and Behrendt, 2011; European Commission, 2010; National Research Council, 2007; Reller et al., 2009). A review of existing criticality studies is presented in (Erdmann and Graedel, 2011). Within these studies, criticality of a material is assessed based on the consequences of a supply shortage of this material and its supply risks. In some studies, environmental implications are added as a third dimension.

According to an EU study 14 materials are to be considered as critical within the EU (if platinum group metals (PGM) and rare earths are each counted as one). In this study, the criticality definition is as follows: "a *raw material is labeled 'critical' when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials*" (European Commission, 2010). The following materials fall under the EU definition (European Commission, 2010):

Antimony	Gallium	Magnesium	Rare Earths
Beryllium	Germanium	Niobium	Tantalum
Cobalt	Graphite	PGM	Tungsten
Fluorspar	Indium		

These materials are of particular importance for a wide range of future and high-tech applications. They are for example essential for batteries (antimony, cobalt), electrical and electronic equipment (EEE) (beryllium, gallium, tantalum,…), special alloys (cobalt, magnesium, niobium, PGM, tantalum, tungsten…), permanent magnets (rare earths), catalysts (PGM, cobalt, germanium, rare earths…) or photovoltaic cells (gallium, tellurium, indium, germanium) among other applications.

The production of most of these materials is concentrated in only a few countries like China (antimony, fluorspar, gallium, indium, rare

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earths, tungsten), DR Congo (cobalt, tantalum) and Brazil (niobium, tantalum). This concentration of production is frequently combined with low recycling rates (European Commission, 2010). This again is accompanied by an increasing demand coming from relatively new technologies like gearless wind energy converters, electric and hybrid vehicles, LEDs, LCDs, etc. (Schüler et al., 2011), which increases the risk of supply shortage even further.

One cause for the low recycling rates of critical materials are high dissipative losses along the life cycle—the critical materials end up in other material flows, get lost in the use phase or elsewhere, and evade recycling. Closing the loops of these metals and avoiding dissipative losses can, however, be considered as an integral part of a sustainable metals management (e.g., Gleich, 2006). This requires detailed knowledge about the flows of metals, though. The other way around, it can be said that knowledge about dissipative losses is of great value from a resource conservation standpoint (e.g., Lifset et al., 2012).

While for some metals, detailed material flow analyses have already been carried out, like for example for gold and palladium from electronic waste (see Chancerel, 2010; Chancerel and Rotter, 2009a, 2009b) or for PGM (see Hagelüken, 2005; Hagelüken et al., 2005) there seems to be a lack of knowledge for most critical materials with respect to dissipative losses (cf. Schüler et al., 2011). In general, dissipative losses are seen as important "loop holes", but there exist no universal definition for the term, nor are there any methods for quantifying the type and the degree of dissipation. Lifset et al. (2012) emphasize this as well by concluding that "*consensus about the nomenclature has yet to emerge and syntheses of knowledge about dissipative flows are quite limited*".

There are also some existing studies dealing (explicitly or implicitly) with dissipation of non-critical materials (depending on the applied definition of criticality and the respective system under study). Within these studies dissipative losses are assessed for example for nickel (Eckelman et al., 2012), silver (Eckelman et al., 2007) or copper (Erdmann et al., 2004; Lifset et al., 2012; Ruhrberg, 2005; Wittmer, 2006). However, these studies consider only dissipative losses into the environment (and some to landfills) and mostly do not distinguish between different types of dissipation. Also, a differentiation regarding the severity of different types of dissipation is not applied and critical materials, like the ones from the EU study, are usually not considered in these studies. Also, in their review of anthropogenic metal cycles, Chen and Graedel (2012) showed that there are hardly any material flow analyses on critical materials. A relatively new addition to the literature on dissipative losses of critical metals is the MaRess study by Wittmer et al. (2011).[1] Here, several critical metals (Ga, Au, In, Pd, Ag) have been assessed regarding their losses into either the environment or "other sinks". Where data was available, Wittmer et al. quantitatively describe the amount of metal lost during all life-cycle stages (from mining to recycling) and the shares of the respective loss-pathways are given. There is no general quantitative assessment of the severity of losses, but annual losses are compared to annual production as a reference, thus leading to a (relative) qualitative assessment. Also other studies differentiate between receiving media of losses, but without paying attention to the dissipative (or not-dissipative) nature of the losses. This has for example been done by Mao et al. (2009) where losses of lead to tailings, slag, fabrication and manufacturing, and landfills are considered. A similar framework has also been applied by Reck et al. (2008) for nickel and Du and Graedel (2011c) for rare earth metals.

Going one step further than Wittmer et al. (2011), we suggest a method to classify and prioritize dissipative losses based on the life-cycle stage of occurrence and the receiving medium. The severity of the dissipation is then assessed from several aspects of the dissipation. This method can be used as a helpful supplement to the "conventional" criticality assessment. Furthermore, when applied, it allows identifying the most important loop holes for optimizations of a product's (or material's) life cycle.

In addition, an exemplary assessment based on a review of literature sources and scientific papers has been carried out, quantifying dissipative losses on an aggregate level for critical materials according to the EU study. Here, a qualitative classification into the proposed categories of dissipative losses is performed, too, with some limitations due to data availability.

2. Material dissipation

Dissipation is a symptom of inefficient open material cycles. Dissipative losses are losses into the environment, long- or short-term anthropogenic stocks, other material flows, or a combination of these. They occur in a way that the receiving medium only contains small concentrations of the material in question (cf. Gleich, 2006; Gößling-Reisemann and Gleich, 2008; Gößling-Reisemann et al., 2007), thus making the recovery impossible or at least technically and economically unattractive. These losses occur in raw material extraction, manufacturing and disposal of a product as well as during the use phase where the application of the product can lead to emission of material into the environment or into other material flows, making recycling (almost) impossible (cf. Scharp, 2009). Based on these characteristics, we propose the following definition for dissipative losses for metals (it might or might not apply to other materials):

> *Dissipative losses are 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.*

The technical and economic feasibility is depending on the current technical knowledge and market situation for the metals under assessment and is thus dynamic. For the definition of dissipation this implies a dynamic element: losses that must be labeled dissipative today might be less dissipative in the future. Since we aim at an assessment of the severity of the dissipation of metals, we must define what we understand by "severity". Regarding the above definition, a dissipative loss must be considered more severe than another, when the recovery of the dissipated metal is less feasible.

2.1. Main drivers of dissipation within the considered life-cycle stages

There are three main drivers for the relatively high dissipation of critical metals between the life-cycle stages of manufacturing and end-of-life treatment: relatively low concentrations of these metals compared to other materials in the final products, ineffective collection and recycling systems, and the use in applications that are explicitly dissipative.

These aspects are mainly caused by the inherent abilities of most critical materials. Even in smallest quantities they fulfill certain functions that are required in many high tech applications and future technologies. Due to their low concentrations they are in most cases not recovered during recycling processes. Use in coatings, EEE, smart labels and alloys among others are examples for this. Furthermore, there are applications that are dissipative themselves, e.g. use in fertilizers, pesticides, or diesel additives.

2.2. Types of dissipative losses

Dissipative losses can occur at every step of a materials' lifecycle: extraction of raw materials, metallurgical refining, production of semi-products, manufacturing of products, use phase, collection and dismantling of products, and the final stages of recycling, incineration or landfilling. The destination of the dissipated metals is threefold: environmental media (air, soil, water), other material flows within the

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[1] This study has only recently been published.