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Effects of circular measures on scarce metals in complex products – Case studies of electrical and electronic equipment

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ABSTRACT

Circular measures such as long-life designs, reuse, repair and recycling have been suggested for prolonging scarce metal life cycles and reducing the dependence on primary resources. This paper explores to what extent circular measures could mitigate metals scarcity when adopted to complex products. Based on three real cases, the effect of extending the use of laptops, smartphones and LED systems before recycling are assessed for between 7 and 15 scarce metals using material flow analysis. As expected, benefits can be gained from such extensions, but, importantly, differ substantially between metals since they occur in various components with various service lifetimes and functional recycling rates vary. Notably, risks of flipping the ranking in favor of short use before recycling are identified: if service lifetimes are short, designs are metal-intensive or if metal contents differ between products. Furthermore, regardless of measure, sizable and varying losses of each metal from functional use occur since all products are not collected for recycling and all metals are not functionally recycled. Thus, neither use extension measures nor recycling can alone nor in combination radically mitigate metals scarcity and criticality currently. Overall, it is a challenge to target the multitude of scarce and critical metals applied in complex products through circular measures. Careful analysis beyond simplified guidelines such as öR frameworks” are recommended. As the importance of scarce metals availability and the attention to the circular economy are expected to continue, these insights may be used for avoiding efforts with unclear or minor benefits or even drawbacks.

1. Introduction

Through advances in technology and materials engineering, most metals in the periodic table are used in today's products (Greenfield and Graedel, 2013). Materials, components and products draw on an increasing diversity of metals, used in minor proportions and in complicated compositions (Graedel et al., 2015; Schulz et al., 2017). As society's demand for functions provided by metal-containing products increases, so do concerns about the risk for metals' limited availability, or scarcity. In the shorter term, scarcity can result from technical, economic or other constraints on extraction, especially in combination with rapidly increasing demand. The risk of scarcity can be geographically delimited, affecting largely import-reliant regions. Accordingly, certain metals and minerals of high economic importance are suggested to be critical for Europe, USA and Japan (EC, 2010, 2014, 2017; Hatayama and Tahara, 2015; Schulz et al., 2017; US-DOE, 2011). For individual firms scarcity risks may typically materialize as supply disruptions and price volatility (Ashby, 2016). In the long term, continued extraction depends on decreasingly concentrated ores which are "mostly non-renewable on human time scales and […] inherently finite" (Schulz et al., 2017). Metals, with the exception of the most abundant ones such as aluminum, iron, magnesium and titanium, can be considered as geochemically scarce with average concentrations below 0.1% of the continental crust (Skinner, 1979). Thus, physical scarcity of non-renewable resources, at some point in the future, is a concern, although there is great variety in its perceived immanency and seriousness (Ayres and Peiro, 2013; Drielsma et al., 2016; Sverdrup et al., 2017; Tilton, 2003). In sum, metals can be considered as scarce for various reasons. Linked to metal use are also substantial environmental impacts, especially those resulting from life cycle energy use and locally from mining (UNEP, 2013a), and social impacts, of which the conflict minerals are extreme examples (OECD, 2013). Hence, the rationale for studying scarce metal use does not only lie in risks of scarcity, but also in other impacts associated to their life cycles.

To reduce the dependency of scarce primary metal resources, substitution to more abundant ones or more efficient management of metal life cycles are required. Accordingly, the circular economy is gaining momentum in policy and business with expectations on increased

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resource availability as well as environmental impact mitigation and boosting of economies (EC, 2015, 2018a; EMF, 2013; Lazarevic and Valve, 2017). The European union has declared critical raw materials (CRM) as one of the priority areas in its action plan on the circular economy and suggested measures over the full life cycles (EC, 2015).

Although material recycling in general can be argued as more established than measures for use extension, scarce metals' functional recycling rates are often low or close to zero (Graedel et al., 2011), meaning that large shares of metals are not recycled so that their properties can be utilized again (Graedel et al., 2011; Guinee et al., 1999). Instead, they are lost through dispersion in recycled materials or in other non-recovering fates (Andersson et al., 2017; Zimmermann, 2017). Thus, a variety of use extension measures *before* recycling can be motivated: design for longevity, sharing, maintenance, reuse, repair, remanufacturing and repurposing. In surging "R frameworks" in the circular economy literature, use extension measures are, with various granularity, ranked before recycling (Kirchherr et al., 2017; Reike et al., 2018). Well-known examples are the waste hierarchy (EC, 2008) and the circular economy "butterfly" diagram (EMF, 2013). But even if environmental benefits of use extension in general has so far mainly been confirmed through life cycle assessments (LCA) (ISO, 2006a, b), assessments point to large variations in benefits, including cases of increased impacts, trade-offs between different types of environmental impact and dependence on product characteristics (Böckin et al., 2018). Thus, the general validity of rankings of measures as in "R frameworks" is not uncontestable. In addition, studies examining real-world cases of such measures are still in short supply (Bakker et al., 2014; Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Korhonen et al., 2018), especially those that describe circular configurations with measures in sequence or parallel (Blomsma and Brennan, 2017). Notably, besides an LCA on shifting to commercial reuse (André et al., 2019), there is a lack of studies on how various scarce metals benefit from shifts to use-extension measures before recycling. This is problematic because actors targeting metals scarcity might risk initiating efforts that cannot achieve the intended results.

Hence, this paper aims to explore to what extent use extension measures before recycling may mitigate metals scarcity in practice. Against the background of the increasing diversity of metals in products, it aims in particular to investigate and explain any differences between metals. This is done by comparing the net loss of multiple scarce metals from functional use in three real-world cases using material flow analysis (MFA) (Brunner and Rechberger, 2004) while explicitly considering product complexity. Functional use is, as a parallel to functional recycling, defined as a use in which a constituent's properties (here metal) are continuously utilized. The cases comprise one business-as-usual (BAU) alternative, based on shorter use of products followed directly by recycling, which is compared with one of extended use before recycling: reuse, repair and long-life products. The latter alternatives are based on existing niche-type and commercially viable solutions. These businesses largely operate on certain electrical and electronic equipment (EEE), why the study specifically compares BAU alternatives with reuse of laptops, repair of smartphones and long-life LED systems. The products are thus high-volume EEE, employing multiple scarce metals for which they, despite concentrations often below ppm levels, represent significant end uses (Licht et al., 2015; Ljunggren Söderman and Ingemarsdotter, 2014). However, the study is not an exhaustive investigation of these specific products nor of the potential for up-scaling the cases. Instead, it investigates a selection of different types of circular measures and aims for general conclusions on real-world opportunities for circular measures involving longer lifetimes, reuse, repair and recycling to mitigate metals scarcity when adopted to complex products. On this basis, implications for metals scarcity mitigation are discussed.

2. Product complexity

Most metals are typically used in a variety of applications and, vice versa, applications make use of a variety metals. One study, mapping 34 metals and 24 applications, identified on average nine metals per application and six applications per metal (Ljunggren Söderman and Ingemarsdotter, 2014). Others made similar observations (Chancerel et al., 2013; Ciacci et al., 2015; EC, 2010; Hagelüken and Meskers, 2009; Talens Peiro et al., 2013). Actual end uses are in fact much greater, since listed material and component applications can be utilized in numerous products. Thus, efforts for mitigating metals scarcity need to consider, on the one hand, the distribution of individual metals over various end uses and, on the other hand, the multiple metals in many end uses. This study concerns the latter, addressing measures adopted to multi-metal products.

Multi-metals use is an indication that an application represents or is a part of a product that can be considered complex. Although product complexity seems to be increasingly referred to, its impact has mainly been assessed as regards material recycling (Bellmann and Khare, 2000; Dahmus and Gutowski, 2007; Friege, 2012). But product complexity could also impact opportunities for measures extending the use of products and components. In that context, the complexity of a product could be represented by the number of parts (Grübler, 2003). But we argue that a more nuanced representation in a hierarchical structure ranging from *product* to *component* to *material* to *substance* to *element* (GASG, 2016; Huisman et al., 2016) is required. Based on this, we suggest that the degree of *physical* product complexity is represented by the physical variety at each such level. Thus, the higher the variety at each level, the higher the physical complexity of the product. Product complexity can however be discussed in more dimensions (Hobday, 1998). Accordingly, we suggest the inclusion of a *product chain* dimension that reflects variety in aspects such as the spatial location and sequence of supplies, manufacturing, end uses and end-of-life fates. In addition, we suggest a *temporal* dimension that reflects the duration of specific states in the physical and product chain dimensions. The larger the variety in duration, the higher the complexity in the temporal dimension. Because of the multidimensional character and variety, numerous combinations are possible. Thus, complex products tend to occur in a variety of designs and over a variety of product chain pathways, at each point in and over time. Although refraining from quantifying product complexity, we suggest that EEE, cars, buildings and airplanes are typical representatives of complex products in line with other suggestions (e.g. Hagelüken et al. (2016), 2016; UNEP (2013b)). Departing from this conceptualization, the study addresses some variety in the three dimensions of product complexity (Section 3).

3. Methodology

The three cases, which substantially expands on case studies in André et al. (2016), were designed with support from the respective companies (Sections 4.1–4.3). Each case compares two alternatives for providing the same function of either laptop use, smartphone use or LED system use. The BAU alternative is mainly based on shorter use of products followed directly by recycling. The use-extension (EXT) alternative involves reuse, repair or long-life products before recycling, modelled on the conditions around the respective companies.

Using MFA, alternatives are compared from product input to output from end of life (EOL), delimiting the compared systems to the product life cycle "from gate to grave" (step 1, Fig. 1). In a second step, the compared systems are expanded to the entire life cycle "from cradle to grave" by adding "from cradle to gate" (step 2, Fig. 1). Temporally and spatially, the systems cover the entire life of the product without further resolution in time and space. Since the entire life is assessed, no stocks are accumulated within the systems.

As a measure of metal scarcity mitigation, the net loss of a metal from functional use, which represents the share of the input that is not

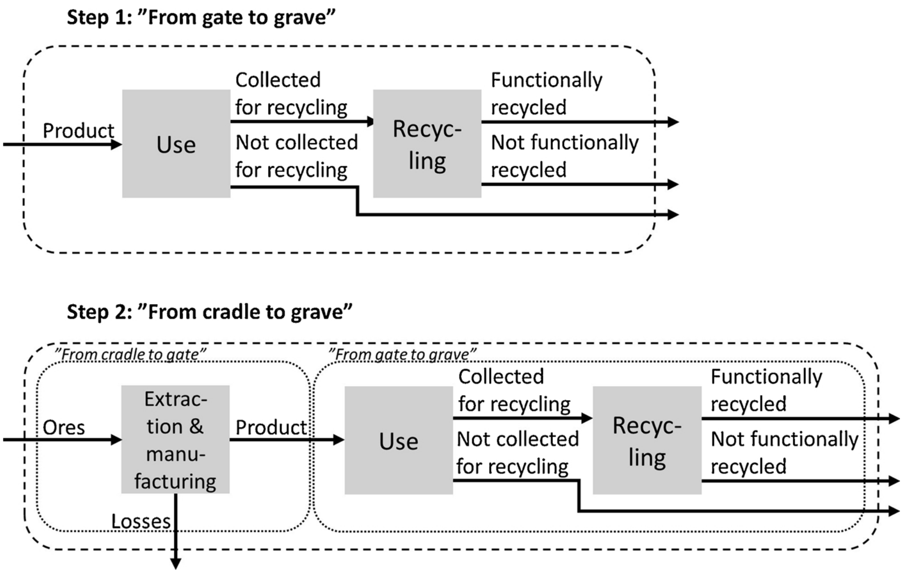

Fig. 1. Simplified system representations in the two steps of the assessment.

functionally recycled at EOL, is calculated as:

$$\textit{net loss}_{i,j,k} = \textit{content}_{i,j,k} \times \textit{system loss rate}_{i,j,k} \tag{1}$$

where i is metal element, j is product or component and k is BAU or EXT. Since lifetimes of alternatives differ, net losses per period of provided function are calculated as:

$$\textit{net loss per period of function}_{i,j,k} = \frac{\textit{net loss}_{\ i,j,k}}{\textit{function}_{j,k} \times \textit{service lifetime}_{j,k}} \tag{2}$$

where service lifetime is the period during which function is provided to a user, thus excluding inactive periods of storage (Thiébaud et al., 2018). Because of their presumed impact or uncertainty, sensitivity analyses of the impact of service lifetime are conducted in all cases and the impact of content and collection rates in one case each.

The relative net loss is then calculated with the content input per period of function in the BAU alternative as reference:

$$\textit{relative net loss}_{i,j,k} = \frac{\textit{content}_{i,j,k}}{\textit{content}_{i,j,BAU}} \times \frac{\textit{function}_{j,BAU} \times \textit{service lifetime}_{j,BAU}}{\textit{function}_{j,k} \times \textit{service lifetime}_{j,k}} \times \textit{system loss rate}_{i,j,k} \tag{3}$$

on which the comparisons of alternatives are based. Eqs. (1–3) describe the general principles, from which sets of equations used for assessing each case were derived (Supplementary Information (SI)). The three dimensions of product complexity are reflected in the equations. The physical dimension is reflected through the physical hierarchy level assessed: reuse at the product level, repair and extended service lifetimes at the component level and recycling at the element level. The product chain dimension is reflected through the efficiencies of activities over the life cycle, such as rates for reuse, collection and functional recycling. The temporal dimension is reflected through the duration of product chain activities, such as the realized service lifetimes.

The second step repeats the comparison of alternatives but of systems expanded to "from cradle to grave" in which losses in primary metal extraction and manufacturing are also considered (Fig. 1). The significance of such losses varies between product chains: examples indicate losses ranging from many times larger to smaller than product input (Licht et al., 2015; Ueberschaar et al., 2017; Zimmermann, 2017). Instead of comprehensive product chain-specific mapping of such losses, we study if extending the systems to the full "cradle to grave" affects the comparison of net losses when "cradle-to-gate" losses are assumed to be very large. This represents the upper boundary of the impact of such losses, while the "from gate to grave" represents the lower. In-use dissipation (Ciacci et al., 2015; Zimmermann, 2017) of the metal applications studied and metals used in supporting processes, such as transports and electricity generation, are assumed negligible.

All data used for the calculations is presented in Sections 4.1–4.3. The first type of data concerns occurrence of metal elements in products, components and materials and build on literature data. Second, product configuration data, used in one case, builds on company data. Third, service lifetimes of products and components build on company and literature data. Fourth, transfer coefficients for activities build on the companies or on conditions in North Europe where the companies primarily operate. Note that the use of a reference cancels absolute values for metal content, function and service lifetimes. The availability of data on metal occurrence at the required product hierarchy level and transfer coefficients for activities were decisive for what metals could be included. Despite the choice to only conduct relative comparisons, insufficient data on occurrence and distribution over components limited the scope. Hence, neither full metal coverage nor full metal alignment between cases were possible. All metals are in the critical raw materials (CRM) candidate lists of the European Union (EU) or Sweden (EC, 2014, 2017; SGU, 2014).

4. Data and assumptions

4.1. Reused versus new laptop

The case compares reused and new laptop computers per period of laptop use. "Reused laptop" (EXT) draws on a resale company, which acquires used IT equipment from professional users. More than 200 000 items are resold yearly - the majority around three years old and without other handling than cleaning and control of data security and functionality (Pettersson, 2016). Reuse is assumed to extend the use of 76% of sourced laptops, while the remaining share is sent to recycling (Pettersson, 2016). Resold laptops, covered by warranty, are marketed "as new" and thus assumed to be equally functional to new ones with service lifetimes doubled (André et al., 2016; Pettersson, 2016). This would in absolute terms correspond to a total lifetime of six years (André et al., 2016; Pettersson, 2016) so that the high-grade segment is slightly above reported average lifetimes (Bakker et al., 2014; Hennies and Stamminger, 2016; Tecchio et al., 2018; Thiébaud et al., 2018). After final use, 50% of laptops are assumed to be collected for recycling from users (Buchert et al., 2012), while 50% follow other pathways without scarce metal recycling. In "New laptop" (BAU), new laptops provide the same function. After final use, the pathways to recycling and other fates are equal to those after final use of reused laptops.

Table 1
Data for laptops (Bangs et al., 2016; Buchert et al., 2012; Cucchiella et al., 2015; Graedel et al., 2011; Götze and Rotter, 2012; Ljunggren Söderman and Ingemarsdotter, 2014).

Component	Element occurrence in “New laptop: BAU” and “Reused laptop”	Element content in “New laptop: component shift” [% of content in “New laptop: BAU”]	Element content in “New laptop: declining metal content” [% of content in “New laptop: BAU”]	Reuse rate [%]	Functional recycling rate (pre-processing and final recovery) [%]
Battery	cobalt (Co)	100	100	76	77
Printed circuit boards	gold (Au)	100	0	76	76
	silver (Ag), palladium (Pd)	100	100	76	76
Platters	platinum (Pt)	100	100	76	0
Capacitors	tantalum (Ta)	100	100	76	0
Magnets	dysprosium (Dy)	0	100	76	0
	neodymium (Nd)	30	100	76	0
	praseodymium (Pr)	47	100	76	0
Illumination	cerium (Ce), europium (Eu), gallium (Ga), gadolinium (Gd), indium (In), yttrium (Y)	100	100	76	0

Gold (Au), silver (Ag), palladium (Pd) and cobalt (Co) are assumed to be functionally recycled (Buchert et al., 2012). Other scarce metals are not assumed to be functionally recycled, as their recovery from post-consumption waste is negligible on an industrial scale (Buchert et al., 2012; Graedel et al., 2011; Götze and Rotter, 2012; Ljunggren Söderman and Ingemarsdotter, 2014).

Since the laptops are physically identical, metal occurrence reported at the product level is used for comparing “Reused laptop” and “New laptop”. Currently, resold laptops are equipped with hard-disk drives (HDD) and screens with liquid crystal displays (LCD) illuminated by light-emitting diode (LED) backlights (Pettersson, 2016). In total, 15 metals could be accounted for (Buchert et al., 2012; Cucchiella et al., 2015) (Table 1).

Sensitivity analyses of reused laptops’ lifetime and new laptops’ contents are conducted. The latter includes two additional versions including technology shifts known to affect metal content. In “New laptops: component shift”, the second new laptop has a solid-state drive (SSD) instead of a HDD, resulting in fewer permanent magnets so that SSD laptops are estimated to contain less of some metals than that in HDD laptops without optical drives (Buchert et al., 2012). “New laptops: declining metal content” is inspired by the observed decline in gold content due to miniaturization and new manufacturing processes (Bangs et al., 2016), but studies a hypothetical extreme of such a decline, assuming a gold-free second new laptop.

4.2. Repaired versus new smartphone

The case compares repaired and new smartphones per period of smartphone use. “Repaired smartphone” (EXT) draws on a repair company partnering with insurance companies to acquire damaged goods (Jarbin, 2016). Insurance holders send damaged smartphones to the company which verifies the damage, and in 36% of cases, repairs and returns the phones. All remaining phones are assumed to be collected for recycling, although some are in practice shipped for component harvesting at a partner company abroad. Components are assumed to be replaced according to the company’s current average replacement rates (Jarbin, 2016) (Table 2). After final use, the repaired phones are assumed to be collected for recycling from users at the rate of 16% over the full life (Navazo et al., 2014), while the remaining share follows other pathways without scarce metal recycling. The use after repair is assumed to be two thirds of a new smartphone service lifetime (Proske et al., 2016b). In absolute terms, average smartphone lifetimes are reported to around three years (Proske et al., 2016b; Sabbaghi and Behdad, 2018; Wieser and Tröger, 2018). In “New smartphone” (BAU), the same function is provided by new smartphones. Pathways to recycling and other fates after final use are equal to those of repaired ones. Only gold, silver and cobalt are assumed to be functionally recycled (Buchert et al., 2012; Navazo et al., 2014) (Table 2) for the reasons explained in 4.1.

Smartphones are assumed physically identical over the studied period, but the assessment accounts for components replaced during repair. Since component-specific metal content data was mostly unavailable, mainly metals of which a major share could be attributed to specific components in current designs are assessed (Table 2). Due to insufficient data on metal occurrence in components, some replacements were excluded. Due to insufficient data on distribution over components, some metals were excluded (Buchert et al., 2012; Villalba et al., 2012). Sensitivity analyses of the service lifetime of repaired smartphones and the repair company’s collection rate are also conducted.

4.3. Long versus short-life LED systems

The case compares two alternative LED systems per period of provided light in an office. LED systems are typically made up of one or several LED luminaires. Luminaires contain a driver and LED packages, which in turn hold LED dies, interconnection technologies and phosphors (Deubzer et al., 2012).

“Long-life LED” (EXT) draws on concepts marketed by Philips Lighting (Philips-Electronics, 2012) and Aura Light (Broman and Robert, 2017; Franca et al., 2017), where light as a function is sold through a product service system (PSS). In a PSS, ownership is generally retained by service providers, who, incentivized to minimize lifetime costs, design systems for longer lifetime (Tukker, 2015), maintenance and recycling (Peeters et al., 2017). To increase service lifetimes, more LED packages are deployed reducing thermal stress (Bengtsson, 2016; Liu et al., 2009; Silfvenius, 2016), the shorter-life driver is replaceable (Bengtsson, 2016; Casamayor et al., 2015; Philips, 2010; Silfvenius, 2016; US-DOE, 2013) and an automation control system (ACS) using infrared sensors for occupancy detection (Bengtsson, 2016; Rogalski, 2011; Santamaria, 2016) reduces operating time (Roisin et al., 2008). After use, 100% of systems are collected for recycling with other lighting products (Bengtsson, 2016; Philips-Electronics, 2012; Santamaria, 2016).

“Short-life LED” (BAU) is based on conventional product sales where office tenants, assumed to prioritize low purchase price, buy systems of lower quality (Franca et al., 2017) and shorter service lifetime (Santamaria, 2016; Silfvenius, 2016). Systems contain fewer LED packages and are non-modular, as the currently dominant design, so that drivers limit lifetimes of systems (Santamaria, 2016; Silfvenius, 2016; US-DOE, 2013). Since LED systems are currently collected and treated with other lighting products, the collection rate to recycling from users is assumed equal to those, i.e. 50% over the full life (Buchert et al., 2012; Recolight, 2016), while the remaining share follows other pathways without scarce metal recycling.

The recycling rates of gold, silver and palladium are roughly

Table 2
Data for smartphones (Buchert et al., 2012; Jarbin, 2016; Navazo et al., 2014; Villalba et al., 2012).

Component	Elements occurrence	Repair rate [%]	Average replacement rates [%]	Functional recycling rate (pre-processing and final recovery) [%]
Screens	indium, yttrium	36	99	0
Magnets in loudspeakers, ear speakers and vibrators	dysprosium, neodymium, praseodymium	36	(47 + 34 + 10)/3 = 30[*]	0
Battery	cobalt	36	20	77
Unrepaired components	gold, silver	36	0	79
	tantalum	36	0	0
Housing	n.a.	36	74	n.a.
Front camera	n.a.	36	36	n.a.
Charger connector	n.a.	36	30	n.a.
n.a.	gallium, palladium, vanadium	36	n.a.	0

[*] Average rate assuming even distribution over loudspeakers, ear speakers and vibrators.

estimated (Reuter et al., 2015). Other metals are assumed to not be functionally recycled. In the case of rare earth elements (REE) in phosphors, this is motivated by more limited recoverability due to lower content, other design and low current market volumes compared to large fluorescent lamps for which REE recovery potentials are higher (Machacek et al., 2015).

System configurations are based on Aura Light (Bengtsson, 2016) (Table 3), confirming technical service lifetimes against other sources (Casamayor et al., 2015; Santamaria, 2016; Silfvenius, 2016). Both alternatives are assumed to use the same type of phosphor application process, but it can be noted that the phosphor content may differ with several orders of magnitude between process types (Buchert et al., 2012; Deubzer et al., 2012). “Short-life LED” has a typical annual operating time for office lighting (Marwede et al., 2012) which is reduced by 4% in “Long-life LED” through the ACS (Roisin et al., 2008), containing sensors of similar die area as in LED packages (Bengtsson, 2016) (Table 3). A sensitivity analysis of the service lifetimes of long-life LED systems is also conducted.

5. Results

There are net losses from functional use of all metals in all cases, but to varying extents. Net losses “from gate to grave” are larger in BAU alternatives with two exceptions (Fig. 2) as further explained in Sections 5.1–5.3. The system expansion to “cradle to grave” affects the comparison of alternatives only for metals that can be functionally recycled, but without shifting rank of alternatives (Fig. 6), as explained in Section 5.4.

5.1. Reused versus new laptops

Net losses are smaller for all metals in “Reused laptop” than in “New laptops” (Figs. 2 and 3). For metals without functional recycling (cerium, dysprosium, europium, gadolinium, gallium, indium, neodymium, platinum, praseodymium, tantalum and yttrium), this is only due to the extended use since all are fully lost from functional use at EOL in both alternatives (Fig. 3). However, since only the reusable share of sourced laptops is doubled in service lifetime, the reduction is less than 50%. Cobalt, gold, palladium and silver also benefit from use extension, but losses are further reduced due to the reuse company’s efficient collection of non-reusable laptops to functional recycling (Fig. 3).

Other lifetimes of the reused laptop would affect the results, but as long as it is above zero, net losses of metals are smaller in “Reused laptop” than in “New laptops”. At zero, net losses of metals without functional recycling would be equal between alternatives, while net losses of metals with functional recycling would still be smaller because of higher shares collected to recycling.

As a sensitivity analysis, the impact of differences in content between the new and reused laptops is illustrated through two additional BAU alternatives. In “New laptop: component shift” the second new laptop contains an SSD instead of an HDD, which affects the content of dysprosium, neodymium and praseodymium prevalent in magnets. When the SSD laptop’s content of these metals is 13% of the HDD laptop, net losses are equal. SSD laptops are estimated to contain neodymium and praseodymium in remaining magnets well above this break-even (Table 1). But dysprosium is eliminated from the new laptop (Table 1) and thus below this level. Hence, in this alternative, the benefit of a reused HDD laptop holds for neodymium and praseodymium, but not for dysprosium. The hypothetical gold-free second laptop in “New laptop: declining metal content” brings net losses of gold very close to that of “Reused laptop” (31 and 30, respectively). Again, the higher collection rate to functional recycling of non-reusable laptops in “Reused laptop” explains the slight difference. Thus, reuse is clearly beneficial if product contents remain unchanged over time. But if not, the benefit depends on the extent to which a metal is substituted and

Table 3
Data for LED systems (Bengtsson, 2016; Buchert et al., 2012; Casamayor et al., 2015; Deubzer et al., 2012; Liu et al., 2009; Philips, 2010; Rogalski, 2011; Roisin et al., 2008; Santamaria, 2016; Silfvenius, 2016; US-DOE, 2013).

Component	Elements occurrence	Units per luminaire [number]		Technical service lifetime [hours]		Annual operation time [hours]		Functional recycling (pre-processing and final recovery) [%]
		Long-life LED	Short-life LED	Long-life LED	Short-life LED	Long-life LED	Short-life LED	
LED packages:		121	64	58 000	20 000	3264	3400	
A. Dies	A. gallium and indium							A. 0
B. Phosphors	B. cerium and yttrium							B. 0
C. Interconnection technologies	C. gold[*]							C. 50
Drivers	gold[*], palladium, silver	1	1	20 000	20 000	3264	3400	50
ACS dies	negligible in relation to LED package dies	0.25	0	50 000	n.a.	3264	3400	n.a.

[*] One driver contains 100 times the gold of one die (Deubzer et al., 2012).

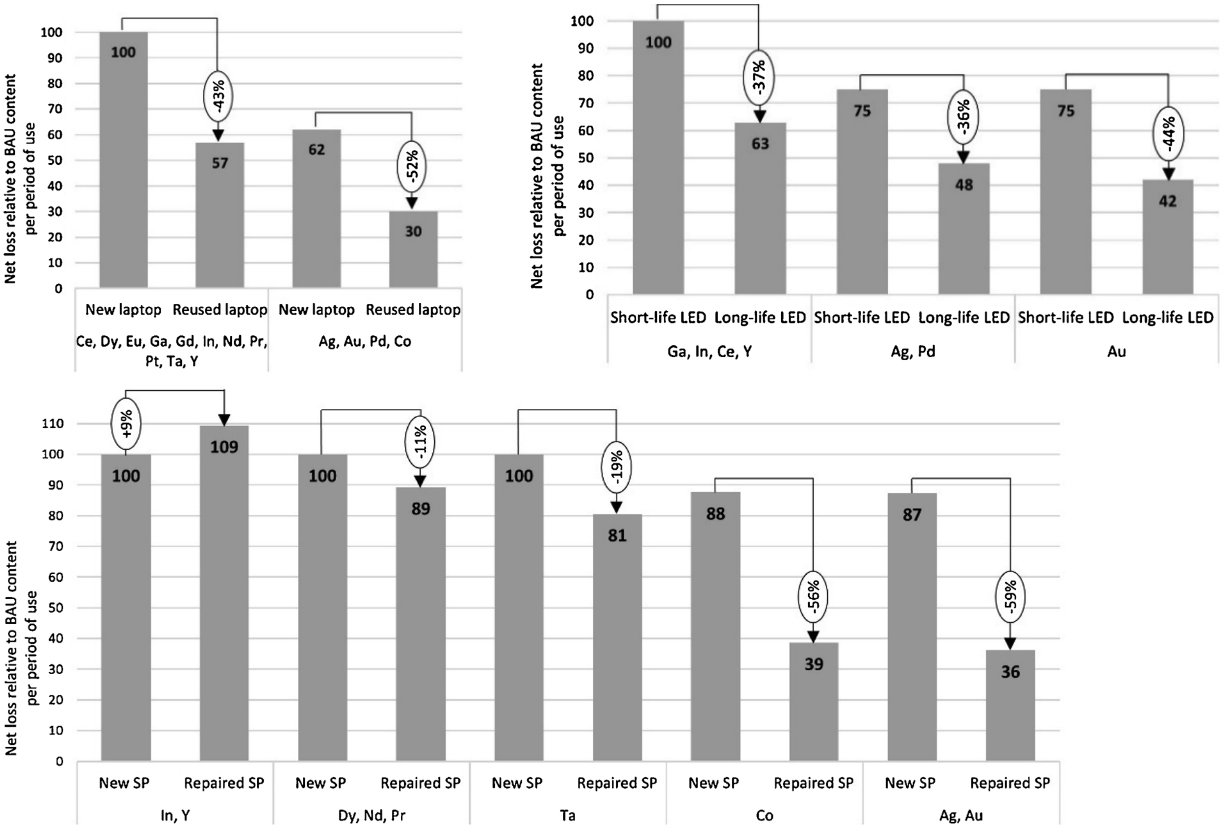

Fig. 2. Net loss of metals relative to BAU product content per period of use, "from gate to grave". Upper left: "New (BAU) vs reused laptop (EXT)". Upper right: "Short (BAU) vs long-life LED system (EXT)". Lower: "New (BAU) vs repaired smartphone (EXT)".

the recycling chain efficiency. Both dysprosium and gold are eliminated, but the ranking of alternatives is only changed for dysprosium. For gold, the higher input per period of use in "Reused laptop" is compensated by a large share of functional recycling.

5.2. Repaired versus new smartphone

Net losses are to various extents smaller in "Repaired smartphone" than in "New smartphone" except for two metals (Figs. 2 and 4). The exceptions indium and yttrium are prevalent in screens, replaced in nearly all repairs, which, combined with a use extension after repair shorter than that of a new smartphone lifetime and a lack of functional recycling, make net losses larger. Net losses of other metals without functional recycling are somewhat smaller as a result of longer use extension: dysprosium, neodymium and praseodymium are in components that are less often replaced, and tantalum is in unreplaced components. In contrast, net losses of functionally recycled gold, silver and cobalt in "Repaired smartphone" are less than half of that of "New smartphone". Repair extends the functional use of gold and silver in unreplaced components and by efficient collection and recycling of unrepairable phones. Cobalt benefits less from use extension since batteries are sometimes replaced but is compensated by efficient collection and functional recycling of batteries replaced and in unrepairable phones, so that net losses are close to those of gold and silver.

Sufficient use extension after repair is crucial for metals in replaced components without functional recycling. The higher the replacement rate, the longer the use extension required for the company's repairs to be beneficial. The sensitivity analysis shows that only at a use extension after repair of 99% of that of a new smartphone lifetime are net losses of indium and yttrium equal between alternatives. Such a breakeven for replaced components containing neodymium, dysprosium and praseodymium is 30%. For unreplaced components containing non-functionally recycled metals (here tantalum), any use extension after repair is beneficial. In contrast, for metals with functional recycling, use extension is not required due to high collection rates to recycling. Thus, the company's handling of discarded items is important for metals with access to functional recycling. At lower collection rates, the difference in net losses of functionally recycled metals between alternatives would be substantially reduced. The sensitivity analysis shows that if the company's collection rate to recycling is as low as that of users (16%), relative net losses of cobalt and of gold and silver increase to 75 and 70, respectively, in "Repaired smartphone".

The benefit of repairing smartphones thus varies substantially between metals. Repairs may not be motivated if use extension is short, replacement rates high and functional recycling lacking. In contrast, if highly efficient functional recycling pathways are in place, long extension after repair is not crucial to motivate repair.

5.3. Long versus short-life LED systems

Net losses are smaller for all metals in "Long-life LED" than in "Short-life LED" (Figs. 2 and 5), but for different reasons. A higher content of gallium, indium, cerium and yttrium is compensated by packages' longer lifetimes, slightly furthered by the ACS, and the modular design keeping them in functional use when shorter-life drivers are replaced. Since these metals lack functional recycling, collection rates to recycling has no effect. The content of silver and palladium are equal and driver operation times differ only slightly due to the ACS. For these metals, the results are instead primarily due to the difference in collection rates to functional recycling between the company and users. Gold contained in packages benefits from longer functional use and a large share of functional recycling, while gold in drivers only from a large share of functional recycling.

Although the technical lifetime of 18 years of LED packages in

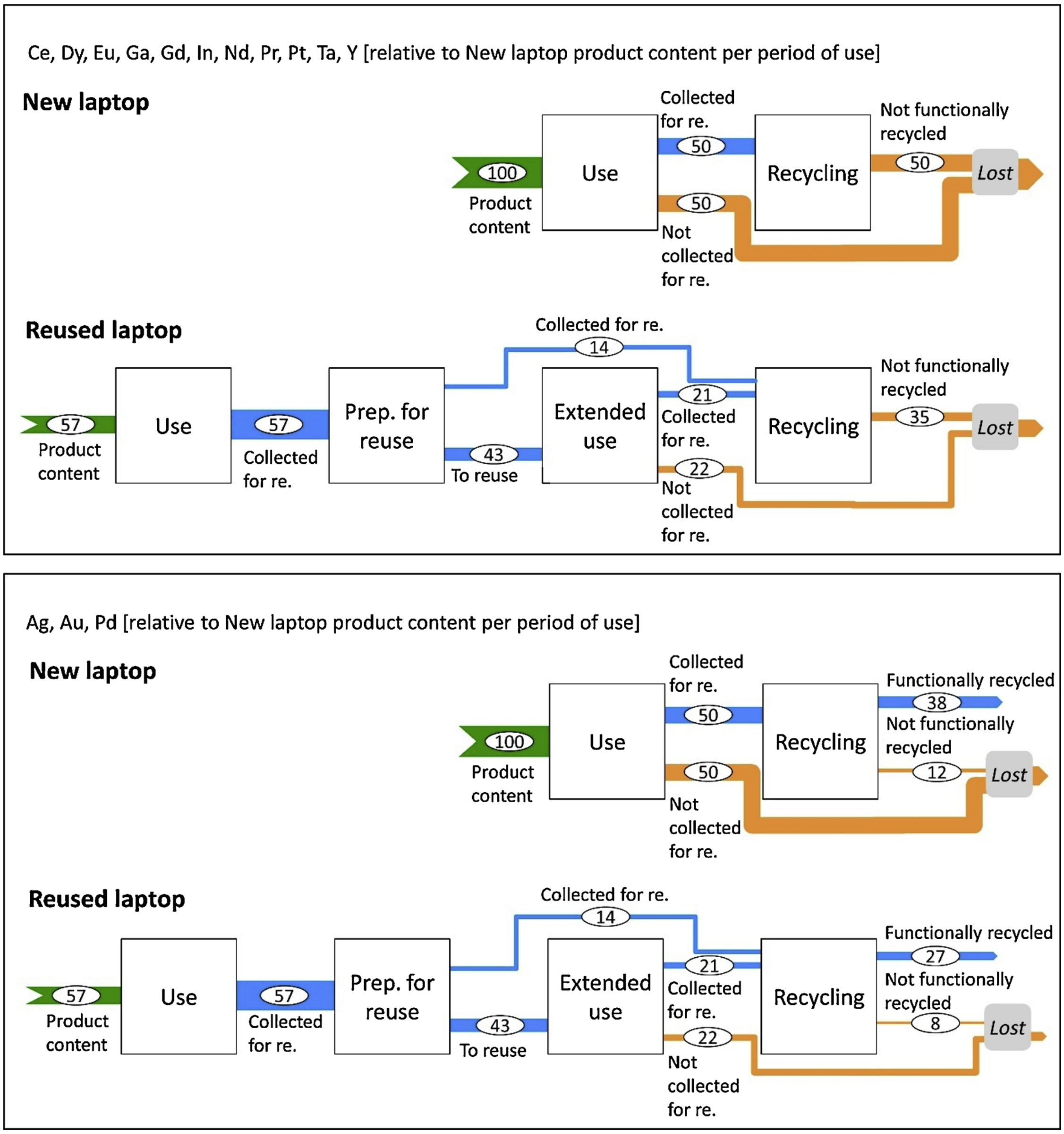

Fig. 3. Metal flows relative to New laptop content (BAU) per period of use, "from gate to grave".

"Long-life LED" reportedly is possible, it risks not being reached in practice if customer and policy requirements change and technology advances. The sensitivity analysis shows that if realized lifetimes in this case are below 11 and 7 years, respectively, net losses of metals in LED packages (gallium, indium, cerium and yttrium, and gold) would be larger in "Long-life LED" than in "Short-life LED". For metals in drivers, there is no such lower limit since their content is equal and efficient collection and recycling already create the major benefits.

Thus, if longer technical lifetimes are enabled by increasing the contents of metals that lack functional recycling, sufficiently realized service lifetimes are required for such designs to be worthwhile. Shorter service lifetimes can be compensated for by highly efficient collection and functional recycling as illustrated for gold in LED drivers.

5.4. Expansion to "cradle to grave"

Extending the system to "cradle to grave" and assuming very large losses "cradle to gate", changes the comparison of net losses for metals with functional recycling, but not for metals without functional recycling (Fig. 6). In all three cases, comparisons then only depend on the metal input per period of use, with negligible benefits from recycling at EOL since the quantity of metals contained in products are negligible in relation to assumed "cradle to gate" losses.

However, for the metals affected by expanding the system (gold, silver, palladium, cobalt), macro-level metal cycle studies show small "cradle-to-gate" losses (Harper et al., 2012; Johnson et al., 2005; Lanzano et al., 2006; Saurat and Bringezu, 2008; USGS, 2004). This suggests that if product-specific data on such losses were used in calculations, comparisons of alternatives would likely be closer to "gate to grave" (Fig. 2) than to "cradle to grave", supporting the focus on comparisons over "gate-to-grave" in the study. But even if "cradle-to-gate" losses do not affect the comparisons, their absolute quantities could be substantial and relevant for resource-efficiency efforts.

6. Discussion

6.1. Implications for metals scarcity mitigation

The study compares real, commercially viable cases of short and extended use of EEE before recycling. The short-use alternatives

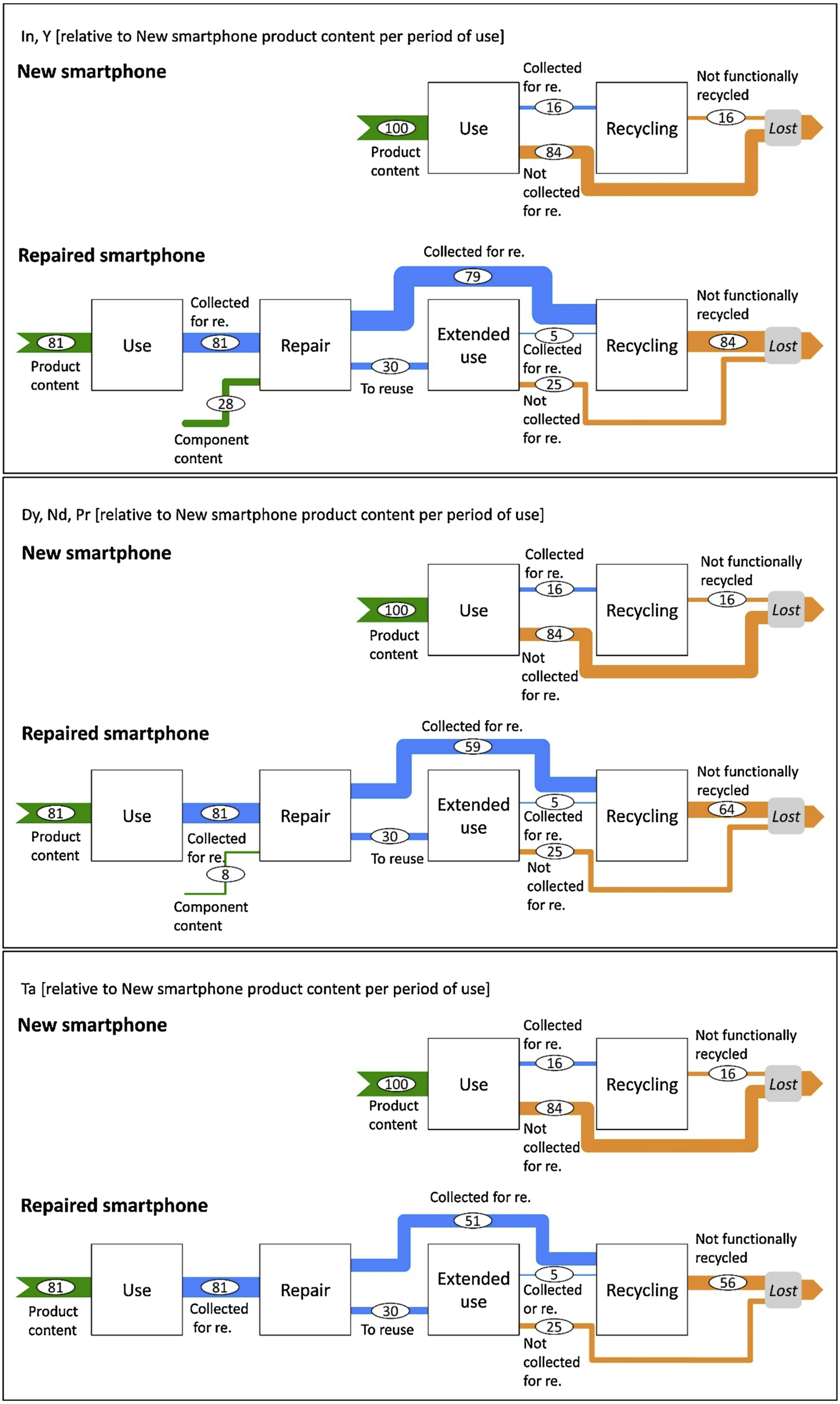

Fig. 4. Metal flows relative to New smartphone content (BAU) per period of use,” from gate to grave”.

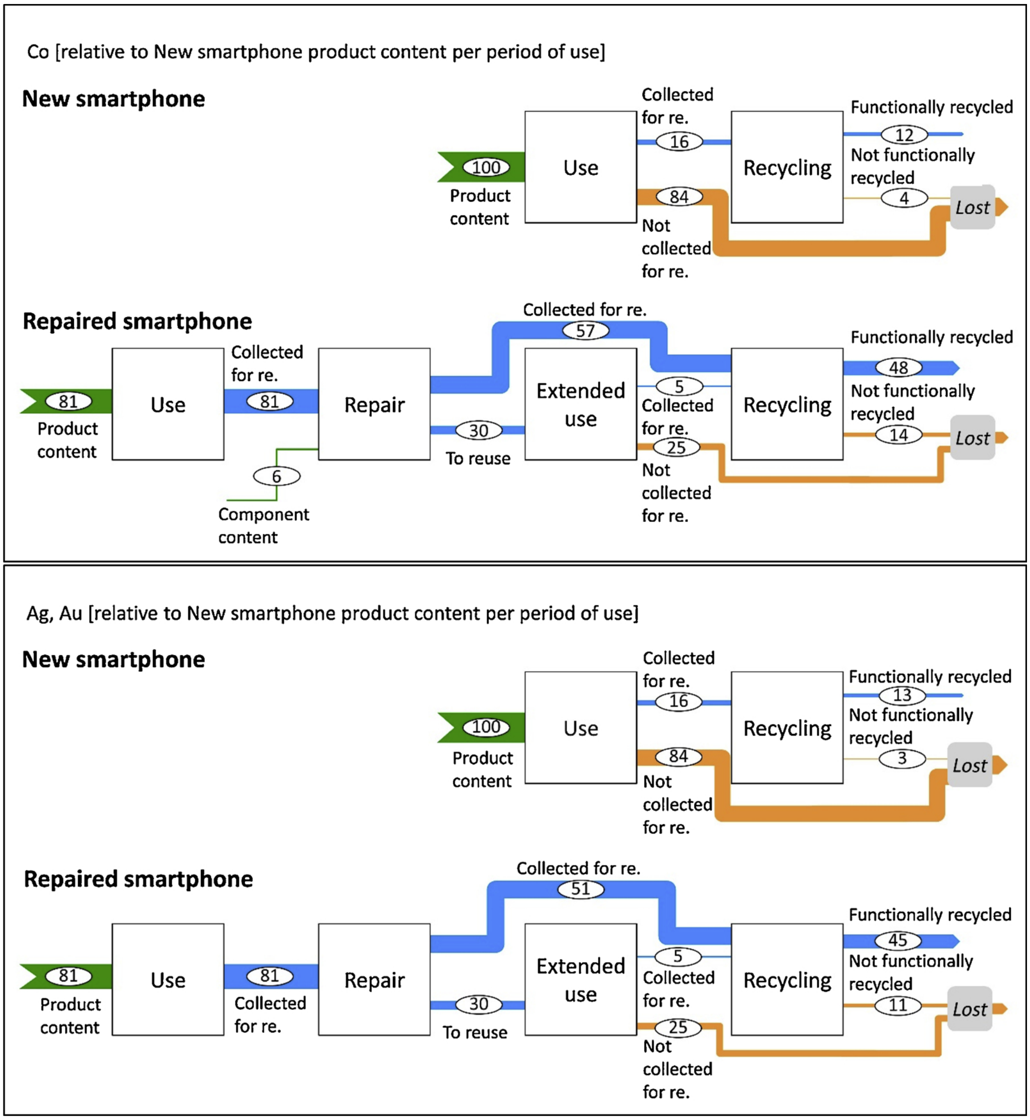

Fig. 4. (*continued*)

represent currently dominating conditions in Northern Europe, while the extended ones are modelled on niche-type businesses in the same region. As such, it adds to the literature of real cases of circular measures. Beyond that, it illustrates the opportunities for circular measures involving longer lifetimes, reuse, repair and recycling of complex products to mitigate metals scarcity.

The real cases are indeed circular configurations consisting of a combination of measures (Blomsma and Brennan, 2017). This affects the results. All six alternatives involve sizable net losses of each metal from functional use (between 44 and 100% of input). These losses occur because all products are not collected for recycling and all metals are not functionally recycled. When comparing the two alternatives in each case, use extension before recycling is preferable, but the benefits differ substantially between metals (between 11 and 59% reduction) and there are two metals for which use extension is indicated to increase net losses (by 9%). Moreover, in the reuse and repair alternatives, far from all sourced products can be extended, with substantial shares directly recycled. When comparing metals within each alternative, differences are explained by the fact that metals occur in various components with various service lifetimes and that metals' functional recycling rates at EOL vary.

The increased net losses of two metals in the smartphone case are due to that component replacement rates are high, service lifetimes of replaced components are shorter than those of new ones and functional recycling is lacking. The break-even analyses point to even more risks of flipping the preference of use extension before recycling. One is illustrated by the laptop case in which the benefit of reuse is affected, even shifting the ranking for some metals, if laptop variants of different metal content are compared. Content differences could be caused by technologies evolving over time, as in the laptop case, but also by simultaneous existing various product segments or manufacturing processes, as indicated by the LED case. Another risk is illustrated by the long-life LED system which relies on a more metal-intensive design and risks increasing net losses of certain metals if service lifetimes are insufficient. Reasons for insufficient lifetimes vary (Cooper, 2010). As an example, the use of long-life LED systems may be cut early by changing consumer requirements or potential conflict with tightening European policy on energy efficiency (EC, 2016a, 2018b). Modular product designs are claimed as enablers for longer use through repair, upgrading and remanufacturing, but could in fact involve risks for increased metal losses if the service lifetime of the replaced component is short, as illustrated by the smartphone case. Also unreplaced modules can involve such risks, if they need to be designed with substantially more metal to enable replacement operations, as in another study of smartphones (Proske et al., 2016a). Thus, design strategies for longer lifetimes can reduce net losses of any metal that completely or partly lacks collection

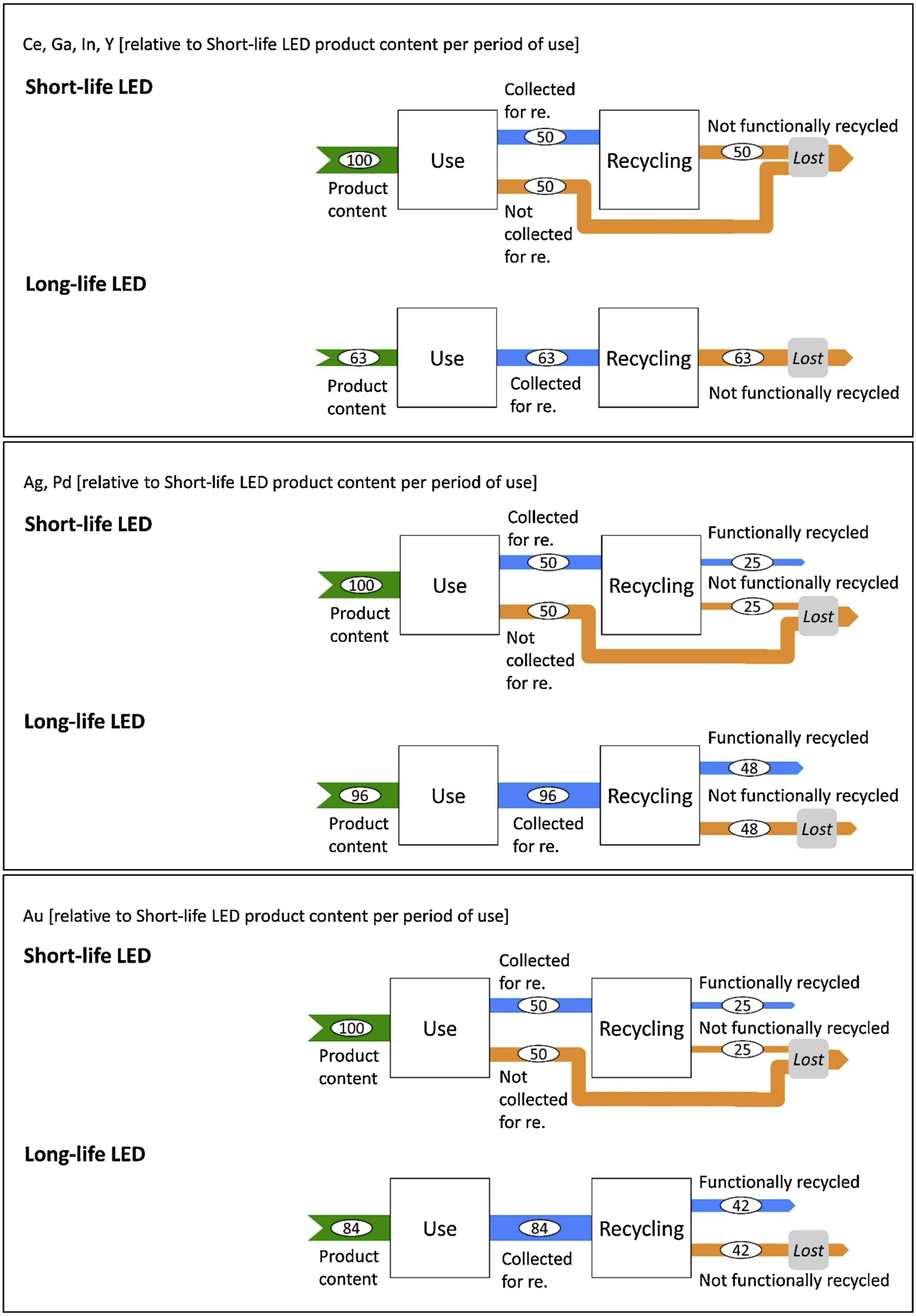

Fig. 5. Metal flows relative to Short-life LED content (BAU) per period of use,” from gate to grave”.

and functional recycling, which in practice currently means all metals. But if such designs rely on increased metal intensity, they may risk larger metal losses.

In sum, the results indicate that, currently, neither use extension measures nor recycling can alone mitigate metals scarcity radically. Use extension measures are beneficial but metals that are unrecycled at EOL are eventually inevitably lost. Also, use extension that requires additional metal input (as may be the case for long-life products, repair,

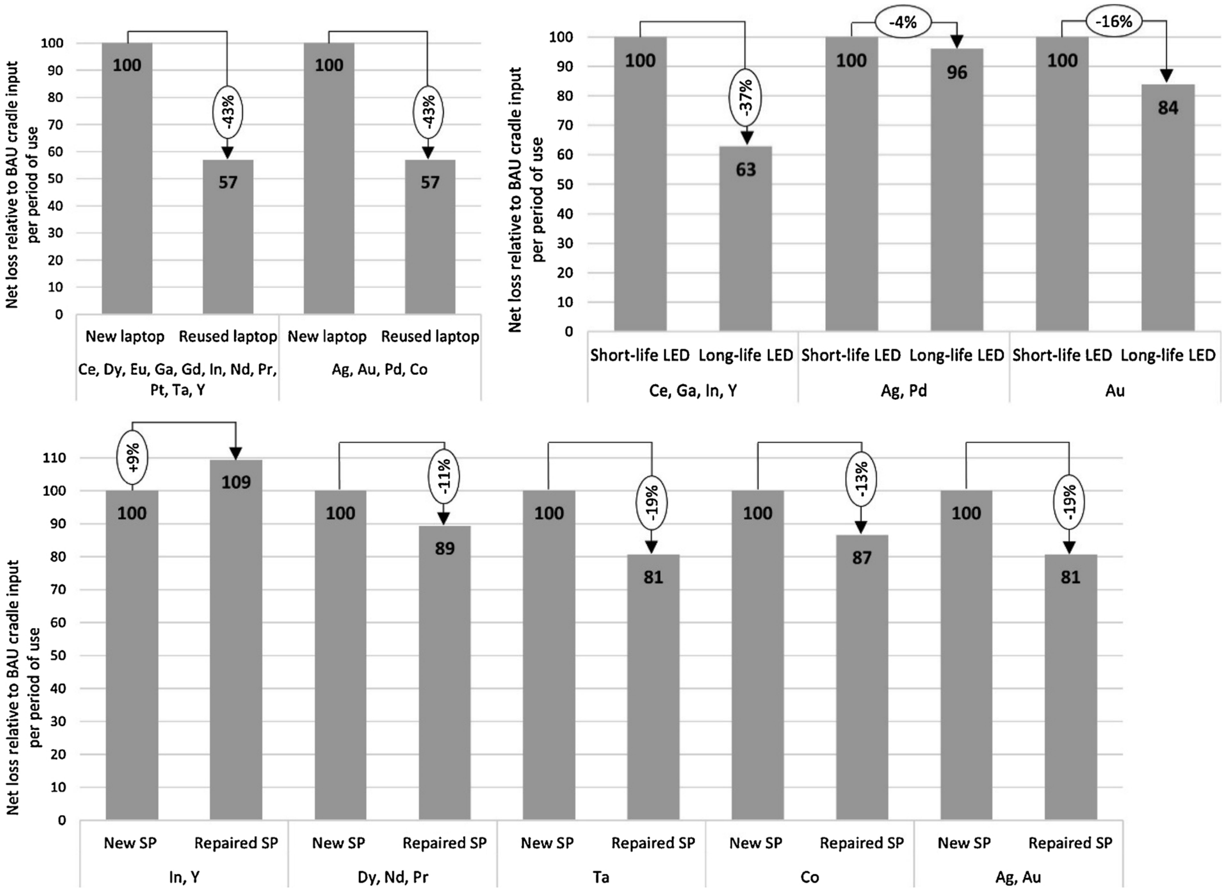

Fig. 6. Net loss of metals from functional use at very large "cradle-to-gate" losses relative to BAU cradle input per period of use, "from cradle to gate". Upper left: "New (BAU) versus reused laptop (EXT)" ("New laptop" cradle input per period of use = 100). Upper right: "Short (BAU) versus long-life LED system (EXT)" ("Short-life LED" cradle input per period of use = 100). Lower: "New (BAU) versus repaired smartphone (EXT)" ("New smartphone" cradle input per period of use = 100).

upgrading and remanufacturing) may involve increased losses. Recycling could potentially circulate metals, but since only the collected share of the most highly valued metals are currently functionally recycled, losses of all metals are considerable. Hence, it is key to support both use extension and recycling. For example, promoting durability, reusability, reparability and recyclability in the European Ecodesign directive (EC, 2009, 2016b) is crucial.

The assessments primarily reflect product complexity in the physical dimension through the variety of elements, components and product variants addressed. Admittedly, the exploration of product chain and temporal dimensions is more limited, reflected through product chain efficiencies and lifetimes. Nonetheless, the study indicates that important insights can be gained by assessing each individual metal at the physical level affected by the measure with corresponding lifetimes and product chain efficiencies. One such insight is that "R frameworks", which typically place recycling as inferior to, in turn, repair, reuse and long-life products, are too simplified for indicating potentials for scarce metal mitigation. Such frameworks depart from idealized single measures implemented in perfect conditions and do not account for physical product characteristics. It cannot be taken for granted that measures are beneficial with respect to every metal nor that their potentials are easily reaped in practice. This observation may also hold for environmental impacts as indicated by the trade-offs between various impact types noted in life cycle assessments (Sections 1 and 6.2). Considering the surge of various "R frameworks" in literature (Kirchherr et al., 2017; Reike et al., 2018) and the risk of interpreting rankings as valid for all resources or all environmental impacts, clarity on their grounds for ranking and their applicability for guiding real-world resource-efficiency efforts is highly needed.

Regarding policy for critical raw materials, the European Union's lists (EC, 2010, 2014, 2017) include palladium and cobalt, which together with gold and silver have the smallest net losses in all cases. The four metals are of relatively high market value and are the only ones to be functionally recycled, but losses from functional use are still substantial (ranging from 44 to 88% of input). Other CRMs studied, such as REE, tantalum, gallium and indium, lack industrial functional recycling and are completely lost after use. Although use extension is currently the only means to improve their management, unless substituted, net losses of such metals are reduced by 43% at the most in the study. This indicates that circular measures can contribute but are far from radically mitigating criticality in current conditions. The differences in results between metals also indicate that trade-offs between CRMs are implicit in policy decisions. For example, assuming that indium and yttrium are prioritized over other CRMs, policy supporting repair of smartphones or other fast products with fragile screens could be questioned. Making such priorities explicit could be the starting point for designing policy that efficiently targets highly prioritized CRMs while others are deliberately lost.

Finally, the cases illustrate that numerous actors play important roles for the outcomes of circular measures. Manufacturers and their tiers of suppliers set important conditions when deciding on product designs. PSS providers design, market and operate the system on sourced components, and may have room for exploiting lifetimes and setting up efficient EOL operations (cycLED, 2015; Tukker, 2015). Reuse and repair are mediated by companies exploiting remaining product value, often independently from manufacturers (Kissling et al., 2013; Whalen et al., 2018) and can stimulate users to both supply and demand products, but have little influence on designs. Their role in securing that items discarded in their activities reach recycling is highly important. Users are central in several respects: they choose what products or services to demand and supply products for use extension. In doing so, users heavily influence service lifetimes and fates of discarded products. Actors in the recycling chain act on what is generated by others, challenged to adapt their activities to often rapidly changing composition and volumes.

6.2. Prospects for further study

Considering the limited scope, but the illustrated usefulness of accounting for how product complexity affects circular measures, its further exploration appears crucial. The conceptualization of product complexity could be developed, and product complexity quantified. Part of this could be studies on content variability in fixed years and changes over time, similar to the study on laptop bill-of-materials by Kasulaitis et al. (2015). Moreover, the benefits and drawbacks of reducing product complexity and product contents of scarce metals merit investigation.

Further work could involve translation of the study's relative comparisons into absolute metal quantities as well as inclusion of omitted metals. This would require extensive additional data on content and distribution of metals in products and components. But it would also enable environmental impacts such as climate change, metal depletion and toxicity to be compared using LCA. This could provide additional insights on, for example, the relative contribution of individual metals to long-term depletion. Another example relates to the observation that highly efficient recycling chains may compensate short lifetimes in terms of net metal losses. This may not hold for climate change impacts since component manufacturing represents substantial shares of impacts for e.g. laptops (Andrae and Andersen, 2010; Kasulaitis et al., 2015) and cannot be offset by recycling of materials (André et al., 2019). Such work would also provide some ground for clarifying the validity of “R frameworks”.

It would also be valuable to examine how a variety of such real and currently niche-type operations may play out at the macro level, assessing their potential in scale and time against other measures. A salient issue is then how to sufficiently account for product complexity at aggregated levels since it substantially affects the outcome of measures.

7. Conclusions

Circular measures have been suggested for prolonging scarce metal life cycles and reducing the dependence on primary resources. Scarce metals are typically used in complex products, which contain multiple metals in various components of various lifetimes and exist in various designs spread over various product-chain pathways, at each point in and over time. This study suggests a conceptualization of product complexity and uses it to explore real-world, commercially viable cases of such measures implemented on EEE, typical representatives for complex products.

Results show sizable and varying net losses of each metal from functional use, regardless of measure. This is because all products are not collected for recycling and all metals are not functionally recycled. As expected, benefits can be gained when introducing use extension before recycling, but, importantly, differ substantially between metals since metals occur in various components with various service lifetimes. Notably, there are risks of flipping the ranking in favor of short use before recycling if service lifetimes are short and designs are metal-intensive or if metal contents differ between products.

Currently, neither use extension measures nor recycling can alone nor in combination radically mitigate metals scarcity and criticality. Use extension is crucial for metals that completely lack functional recycling (11 out of 15 metals studied), but is important also for metals with functional recycling, since all do not reach recycling at EOL. Hence, strategies need to include both use extension and recycling.

Overall, it is a challenge to efficiently target the multitude of scarce metals applied in complex products through circular measures. Careful analysis and implementation, accounting for product complexity in several dimensions is recommended. Guidelines such as “R frameworks” are too simplified for supporting such tasks. Considering that real implementations of circular measures entail sizable metal losses, the opportunities for rethinking product designs and the content of scarce metals in products should also be explored. As the importance of scarce metals availability can be expected to continue and attention to the circular economy increases in business and policy, these conclusions may be used for avoiding efforts with unclear or minor benefits or even drawbacks.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

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