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Metallic resources in smartphones

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53 metallic elements from smartphones were investigated with regard to metal prices, metal production, and content in comparison to mined ores. The metal content of the 7.42 billion smartphone devices sold from 2012 to 2017 could theoretically maintain the global supply for 91 days for Ga, 73 days for Ta, 23 days for Pd, 14 days for Au, and 6 days for REE. The pure metal value of a single smartphone device for the investigated metals currently sums to 1.13 US $; it averaged at 1.05 US $ from 2012 to 2017 with the highest value of 1.32 US $ in 2012. The Au content is low (16.83 mg per device), yet constitutes the highest value with a current share of approximately 72% of total value for all measured metals, followed by Pd (10%). Approximately 82% of total metal value can be recycled with current standard recycling methods for Au, Cu, Pd, Pt, which only comprise 6 wt% of the total device. The printed circuit board (pcb) contains 90% of the measured Au, 98% of Cu, 99% of Pd, 86% of In, and 93% of Ta. The Au, Pd, Cu, Pt, Ta, In, Ga contents in a smartphone pcb are significantly higher than the metal content in currently mined ores. Magnets contain 96% of the measured REE and 40% of the measured Ga, with higher concentrations than ores for REE and Ga. For Co and Ge, metal content in smartphones (w/o batteries) is lower than in ores.

1. Introduction

The functioning and progress of our society highly depends on digital technologies, which dominate our economy and lifestyle. Every technology depends on the availability of processed metals and industrial minerals (Reuter et al., 2013). Future efforts to decrease our carbon footprint, for example, clean energy, and carbon-decreased mobility, heavily depend on the availability of specific raw materials as well. Lately, concerns about supply security have led to an increased interest in studying supply chains. This includes the primary and secondary sectors for availability of mineral raw materials, accompanied by several recent studies published in this field (e.g., Reuter et al., 2013; Graedel et al., 2013; NSTC, 2016; Blengini et al., 2017; Huisman et al., 2017). The key to understanding which raw materials could be utilized in future energy systems lies in estimating the availability of these materials through quantitative assessments and predictions. This study aims at identifying the raw material content in smartphones and its potential to increase the availability of specific metals through recycling.

There exist several terms and definitions to describe the relationship between raw materials, supply chains, and demand (e.g., Erdmann and Graedel, 2011; EU Commission, 2010). The most important of them are “critical raw material” (e.g., Mathieux et al., 2017), “technology metal” (e.g., Reuter et al., 2013), and “technology critical element” (Cobelo-García et al., 2015). None of these terms have a strict chemical definition; these are rather descriptions for elements of economic and strategic importance especially for future technologies, combined with supply risk (Mathieux et al., 2017). A recent review of critical raw material methods can be found in Schrijvers et al. (2020). Although these elements change over time and vary depending on country viewpoint (e.g., the United States of America and the EU have different requirements for materials), elements stated in this list usually include cobalt (Co), gallium (Ga), germanium (Ge), indium (In), the rare earth elements (REE) and tantalum (Ta) amongst others (Bauer et al., 2011; Mathieux et al., 2017). In this paper, the focus is set on metallic elements

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only, hereinafter termed as "metals", although referring to and including metals, metalloids, transition metals and lanthanoids, which could potentially become critical for raw material supply.

In the past years, especially waste electrical and electronic equipment (WEEE) has been identified as a potential metal source and has been widely discussed (e.g., Huisman et al., 2007; Reuter et al., 2013; Graedel et al., 2011; Chancerel et al., 2013). In addition, electrical and electronic equipment (EEE) continues to be one of the fastest growing waste streams (2% according to EU Commission, 2020), which means that the amount of EEE and WEEE will continue to increase (ITU International Telecommunication Union, 2016; EU Commission, 2020). The EU Commission states in the new Circular Economy concept that "value is lost […] when materials incorporated in devices are not recovered" (EU Commission, 2020). Yet, exact data on metal content of (W)EEE are only scarcely available (e.g., see Huisman et al., 2017) and thus, for some devices only vague interpolations for recycling potentials are possible. As metal content in these products varies widely, further analytical data are required for investigations of current and future metal scenarios. Thus, this research focuses on the assessment of content, value, and availability of metals related to one sample technology of EEE that is almost ubiquitous with 1.41 billion devices sold in 2018: smartphones.

1.1. Why smartphones?

By number, a large proportion of (W)EEE is consumer electronics, such as Information and Communication Technology (ICT) devices (EU Commission, 2011). Particular interest lies in mobile phones, as they are often cited as containing many of the "technology" metals (Hagelüken and Meskers, 2010; Reuter et al., 2013), and mobile phones have been the subject of continuous collection and recycling studies (e.g. Graedel et al., 2011; Polak and Drápalová, 2012). The term "mobile phones" comprises common mobile phones (with a keypad instead of a touch display) and smartphones (new generation mobile phones with a large touch display, an operating system to run applications, and internet connectivity). Mobile phones have much larger sale numbers than remaining ICT devices. There are over nine billion mobile phone connections registered with approximately 4.8 billion people using a mobile phone, 3.5 billion of which are smartphone users (ITU in Statista, 2019a). Total sales of all mobile phones have been 11.04 billion from 2012 to 2017 (Statista, 2019a). Smartphones have been overtaking common mobile phone sales since 2014 and thus have become more important (Statista, 2019a). There were 1.41 billion smartphone devices sold in 2018 (out of 1.86 billion mobile phones), and a total number of 7.42 billion smartphones were sold from 2012 to 2017 (Statista, 2019b). Yet, mobile phones in general only have a low global return rate of 5–10% (Graedel et al., 2011; Hagelüken and Meskers, 2010), with high estimated numbers of phones sitting in people's drawer as one often stated issue (e.g., Tanskanen, 2013; Bookhagen et al., 2013). Hence, the collection, i.e., retrieving in general has been and still is one major bottleneck (Reck and Graedel, 2012).

Current public data on exact metal content of newer generation smartphones (after 2010) have not been published (Huisman et al., 2017), apart from a single study by Holgersson et al. (2018). Existing data on older mobile phone metal content (summarized by Sarath et al., 2015) focus mainly on the printed circuit board as the most valuable part of the mobile phone, and describe only up to 20 metals; furthermore, these studies do not cover smartphones. An analytical method based on total digestion and measurement based on mass spectrometry to quantify the abundance of 58 metals in smartphones was developed and fully validated (Bookhagen et al., 2018) to determine the exact metal composition.

In Reuter et al. (2013), mobile phones and laptops sales were already put into context of yearly mineral raw materials demand for some metals (gold (Au), silver (Ag), copper (Cu), Pt (platinum), Pd (palladium), and cobalt (Co)) to show their impact on worldwide metal usage. For example, according to this study, in 2010 Pd for the production of laptops and mobile phones constituted 5% of the global demand. We strive to extent this analysis by determining the share for additional technology metals (such as Ge, Ga, In, Co, Cu, and the REE) specifically used for the production of smartphones and their impact on global metal demand.

In the new Circular Economy Action Plan ("The European Green Deal"), the EU Commission presents several measures to support a sustainable product framework for sectors with high resource use such as EEE (EU Commission, 2020). One of the goals for EEE is "establishing a common European dataspace with data on value chains and product information". Information from our study will add data to the EU circular economy concept by providing novel product data of exact smartphone metal contents, and by adding assessments of current production, supply, and recycling aspects for important metals in smartphones. This data can be used to interpolate future demand and supply of the investigated metals, and can add further insight on future recycling efforts for the aimed circularity and sustainability of products (EU Commission, 2020).

1.2. Metal sources: ore vs. recycling

Metals can be derived from primary or from secondary resources. Primary resources are natural resources such as minerals and ores that have to be extracted from the Earth under given geological, technical, economic, social, and legal conditions. Secondary resources have entered but no longer serve a purpose in the economy; they have been processed and used by humans before and include slags and scrap in general, including old (end-of-life, EoL) and new scrap (processing scrap from industrial productions) (Gunn, 2014). In general, and pertinent for this study and investigated metals, primary resources are ores, secondary resources are slags, scrap, i.e., metals and alloys obtained from all forms of recycling. Extracting metals from primary or secondary resources generally requires physical and chemical processing to isolate the metal in the desired chemical form. In general, metals can be recycled repeatedly (e.g., Gunn, 2014), and in this study, the term recycling refers to the recovery of metals and alloys. Recycling efforts are strongly connected but not limited to economic incentives, in general metal prices; yet decisive factors for the recycling industry include a range of aspects: supply of scrap and metal alloys; characteristics and knowledge of the content of scrap; energy cost and capacity of the recycling facility (Tercero and Soulier, 2018). For metal recycling to be economically viable, the accessibility of EoL-products needs to be considered - close geographical availability and infrastructure, but also willingness of consumers to dispose of their EoL-products at recycling facilities. Design for recycling (i.e., parts and metals can be easily accessed for extraction) and metal content are further key points (Hagelüken and Corti, 2010). Scrap product is much different from ore with up to 60 different elements in a very complex matrix, man-made by combination of metals and compounds, which often has low total, dissipative contents (Hagelüken, 2014). Thermodynamic principles establish the feasibility of a chemical reaction under certain operating conditions and thus are the basis for recycling; e.g., in a metal system with gold and tantalum, only one of the two can be refined – the other will become part of the slag which makes recovery very difficult (Ueberschaar et al., 2017). Reck and Graedel (2012) state the most beneficial actions to improve recycling are increased collection rates of discarded products, improved design for recycling, and the enhanced deployment of modern recycling methodology.

In general, metal recycling increases the material and energy efficiency of product systems throughout the life cycle (Gunn, 2014). Associated environmental impacts and energy consumption of secondary metals are for most metals lower than for primary ores, which would be required to be dug and processed (Pohl, 2011; Gunn, 2014). Yet, this depends on the state the metals is present, and for an economically and ecologically sound recycling at EoL, comparing the metal content of the recycling goods to the primary ore is only one aspect due to the above-mentioned factors. One hundred percent recycling of all metals in a complex matrix is not always technically feasible, nor economically suitable, nor is it always ecologically sound (Reuter and van Schaik, 2012). Comparing the so-called urban mine of smartphones with the metal content in primary production, i.e., a simple "metal content in smartphones vs metal content in ore" as facilitated in this study, cannot and is not intended to grasp the complex issue of recycling and the decisive factors for such. However, the detailed information on how much of which metals are contained in consumer electronics versus their content in primary ores can shade light on future recycling discussions for circularity, as well as clarify public misconceptions about the recycling of smartphones.

2. Materials and methods

2.1. Data base for smartphones

Three models of smartphones released to the market in 2011/2012 (third- and fourth generation smartphone (4G, LTE)) from three different operating systems were chosen, based on highest sale numbers in 2012. Three devices of each model type without batteries were investigated and further processed (referred to as triplicate in this paper). Batteries were not included in this study due to safety reasons. Details concerning method development and validation for quantification of 58 metals in smartphones are given in Bookhagen et al. (2018). All parts of the smartphones were manually separated and processed via microwave-assisted acid digestion for subsequent measurement by inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma optical emission spectrometry (ICP-OES).

For this study, we disregard the elements sodium (Na), potassium (K), and calcium (Ca) due to their low relevance as primary raw materials. Alkali (Li, Be, Rb) and alkaline earth metals (Be, Mg, Sr, Ba) are included in the discussion. A threshold of relevance was set at 0.00001 g total content per element; this affected Tl and Tm with lower amounts than that. Hence, in total 53 metals are discussed in detail in this study.

Total weight of the smartphone without battery is on average 110.76 g (93.16 g, 125.73 g and 113.41 g respectively for each smartphone type). On average, 51 wt-% (43 wt-%, 50 wt-% and 58 wt-% respectively) of the complete devices without battery were quantified. Missing weight will derive mainly from polymers, ceramics, and glasses.

The printed circuit boards (pcb) of each smartphone were quantified to 82 wt-%, 74 wt-% and 84 wt-%, respectively, with remaining weight accounting to polymers. The pcb has an average mass of 15.73 g (12.15 g, 22.76 g and 12.27 g, respectively).

Investigated magnets were derived from loudspeaker, camera, and vibration motor, with loudspeaker magnets being the largest in the investigated devices. Average total magnet weight of all three applications per device is 1.03 g (0.93 g, 1.05 g, 1.12 g, respectively). Magnets are generally not located on the pcb and, depending on device type, mounted in different locations. In the investigated smartphones, magnets for these three applications were REE-magnets of NdFeB-type.

The metal contents of the three different smartphone models were averaged to obtain characteristic values for a general smartphone composition, representative for the smartphone generations of 2012–2017, without battery. A metric ton of heterogeneous smartphones contains approximately 10,800 devices.

2.2. Assessing grades, production data and prices: data base for ores and metals

Raw material data on ores, production and metals were adapted from BGR database (German Federal Institute for Geosciences and Naturals Resources), and the USGS, 2010 mineral commodity information (United States Geological Survey, 2017). At the time of our investigation, production data from 2016 is the most recent and comprehensive data set available (DERA, 2019).Where available, mine production was chosen to provide a best possible comparison with smartphone data, principally to compare the smartphone as an "urban mine" with the primary output of metal from an ore mine. Yet, for some metals, only refinery production data is available (e.g., Ga, Ge, In), which is the production data displaying the total supply of a metal. Refinery production depicts the complete output from refineries and can also include secondary resources, e.g., from old and new scrap, or by-production.

The term by-products refers to metals which are obtained largely or entirely of host metals (companion metals) from geologic ores (Nassar et al., 2015). For example, In is a by-product of tin production, and a mine will not be solely processed for In.

2.2.1. Abundance and grades, metal comparison between mine sites and smartphones

The crustal abundance is an indicator of how "rare" a metal is. There is an important distinction between physical rarity (nature-given by crustal abundance) and economic scarcity (by human-made market forces or lack of technology) (Schulz et al., 2017). Abundances for crustal occurrence vary widely in references, demonstrating the complex measurements and calculations. Here, for crustal abundances, data from Thomas Jefferson National Accelerator Facility, 2020 and USGS are used. There are many more factors involved to determine if an ore is profitable, with concentration above average crustal abundance being only one indicator. Depending on the by- and co-products present in the deposit, the size and depth of the ore body, the mineralogy and consolidation of the material to be mined, technical advances, as well as other decisive factors regarding location (infrastructure, country governance and permitting, work forces, etc.) need to be considered. Moreover, metal demand and metal price are crucial but are by no means constant parameters, as they are only valid at a certain time point (see, e.g., Cox and Singer, 2011).

In this study, the content of metals in currently mined ores is compared with the metal content in smartphones. Ore grades are used from various sources, including BGR, USGS, and available literature to cover the main deposit types of mineral resources that are currently being mined. Grades can vary within meters of an ore body, and were taken from reserve base (the proven content of a currently profitable ore body including part of the resource that might be extractable in the future) instead of resources (the estimated but not proven content of occurrences, no matter if economic) and averaged for each deposit. These represent the most realistic data, as other indicators such as the cutoff grade or Clarke value are mostly theoretical: The cutoff grade is the lowest grade of an ore material considered to be economic for mining (Pohl, 2011). This factor varies significantly in time, cannot always depict the current situation of mining, and cutoff-grades are different for every single deposit. Especially for by-products, there is rarely a cutoff grade available. The Clarke value is the ratio between the content of a valued element in an ore deposit and its crustal average (Pohl, 2011; Cox and Singer, 2011) and due to above listed decisive factors is not an accurate measurement for the current feasibility of mining.

The focus for this study is set on technology metals, hence the metals gold (Au), cobalt (Co), copper (Cu), gallium (Ga), germanium (Ge), indium (In), palladium (Pd), platinum (Pt), the Rare Earth Elements (REE), and tantalum (Ta) were further specified by their natural occurrence (grades, geology and mineralogy) in current mine sites. Comparison of ore grades in primary mineral resources with metal content in smartphones is plotted for the complete device and for the printed circuit board. For REE and Ga, a direct comparison to REE-magnets was added, as 90% of the measured REE and 40% of Ga are located in these magnets.

For most metals, there are insufficient data available to calculate a true average grade in all mined deposits, integrating production data.

Only for copper, Mudd et al. (2013) reflected on 700 + mines sites and thus can give a valid average of mined grades. For all other metals, the range of ore grades for main current productions sites is presented instead.

Data for by-products Co, Ga, Ge, In, REE, and Ta are even less available (Schulz et al., 2017). For example, In has relatively low economic importance for most large mining companies and bypasses disclosure requirements. Due to the fact that by-production operations are commonly fed by concentrates from different deposits and locations, it is difficult to track production back to a specific deposit (Schulz et al., 2017a). In this study, literature research covers main information regarding their estimated grades in ores. For further discussion of by-product assessments, see Gunn (2014), Fizaine (2013), or Frenzel et al. (2015).

For better comparability, all values related to crustal abundance, grades, and smartphone metal content are given in mg/kg (milligram per kilogram), which is equivalent to g/t (gram per ton), often referred to as ppm (parts per million) in literature. Total metal content in smartphones is given in g (gram), when a higher resolution for lower content metals is needed, mg (milligram) is used.

2.2.2. *Prices and market concentration*

Metal prices from commercial sources are part of the BGR database and were used covering a timeframe between 2012 and 2017, the timeframe selected smartphones from this study are representative for (see description in Bookhagen et al., 2018). Yet for recycling data, current metal prices (November 2019) are also of interest, because WEEE generally reach recycling facilities several years after usage time (Graedel et al., 2011).

There are several different specifications for each metal and its application when considering prices.

Prices were generally calculated on the basis of metal content. Metals with different specification were calculated proportionate to their usage in components as far as possible; e.g., silicon in glass is derived from quartz with a price of averagely 55 US $ per ton, whilst silicon on pcbs is derived from electronic-grade silicon (polysilicon with 6 N purity, 99.9999%) to produce wafers for integrated circuits, which at 19,500 US $ per ton has a much higher price. For REE, most REE are located in magnets and thus were calculated using their metal price as opposed to REE in display, where the price for oxides was used.

Importantly, the calculated metal or material value does not equal the material cost of components, such as, for example in case of an integrated circuit. The newest chip generation might have different specifications than an older chip model, yet can still have the same material input with only miniscule divergent content, as doting for integrated circuits lies in the range of 0.5–10 mg/kg. Thus, the metal value calculated in this study are based on the element value (calculated by content) and are not equal to material cost of single components within a supply chain. Therefore, the pure metal value composited in the smartphone is provided, corresponding to a theoretical calculation of the potential metal value which could be recycled if 100% recycling would be possible, comparable to the melt metal value in a coin.

3. Results

3.1. *Smartphone composition*

On average, the three investigated smartphones contain by weight 45% metals, 32% glass, and 17% plastics. Additionally, there were on average 6% of heterogeneous components ("other") which could not be separated mechanically or manually (e.g., bounded plastics and printed wires).

On average, 51 wt-% of the devices were quantified in detail, which covers almost all of the metals components (41 wt-% of the total 45 wt-% metal components) and some parts of the display (10 wt-% of total 32 wt-%). Remaining parts are glass, plastics, and compounds of plastics and metals.

For many of the 53 metals (Fig. 1), averaged total content in the three smartphones is low (each group in descending content weight order):

- Seven metals encompass more than 1 g on average per single device: Fe, Si, Mg, Al, Cu, Ni, Cr
- Eight metals are contained with more than 0.1 g ($0.1 g < x < 1 g$): Sn, Zn, Sr, Ba, W, Nd, Mn, Ti.
- Nine metals are contained between 0.1 g and 0.01 g: Pr, Co, Ta, Mo, Zr, Au, V, Dy, Ag.
- Metal content is below 0.01 g for 29 metals: Pb, Gd, Ga, Nb, As, In, Y, Pd, Li, Er, Sc, Hf, Ho, Tb, Bi, Sb, Pt, Ge, Ce, La, Rb, Yb, Hg, Sm, Be, Lu, Eu, Cd, Te.

The ten most abundant elements comprise 93% of the investigated weight of the 53 metals.

The averaged metal composition and their content range in the three investigated smartphones is further specified in Fig. 2. Some metals show a wide content range; e.g., for Fe, the smartphones contain 31.66 g, 13.62 g and 3.69 g respectively, averaging to 15.98 g. The most important components of smartphones in terms of metals are the pcb and the magnets. Measured NdFeB-magnets contained 19–21 wt-% Nd, 6 wt-% Pr, up to 2 wt-% Gd and 1 wt-% Dy. Detailed mass fractions for each element are given in the **supplemental information**.

3.2. *Metal value of smartphones*

Metal prices varied widely in the past decade. Especially 2012 was a year with high prices for commodities, and many metal prices were at its peaks (e.g., the prices for the rare earth element Eu was 20 times higher than today; In and Sb prices dropped during that time to half their prices). On the other hand, some metals which were not in demand at that time experienced an increase in prices: Due to electric mobility, the price for Li, which is used to manufacture lithium-ion-batteries, doubled during that time; and due to the decline of diesel fueled cars (where Pt is used for the catalysts), the price for Pt dropped, and the price for Pd, used in catalysts for unleaded petrol cars, has more than doubled from 2012.

The concept of pure metal value refers to the elemental content of each metal in smartphones as measured in our study. The calculated pure metal value for all 53 elements based on their fractional content currently sums up to 1.13 US $ in one averaged smartphone device (Nov 2019 prices). When calculated for 2012–2017 (the years representative for the investigated smartphones), the pure metal value averages to 1.05 US $ over this six year price timeframe, reaching the highest value in 2012 with 1.32 US $.

The eleven most valuable elements in smartphones (Nov 2019 prices) based on their fractional content are Au, Pd, Ni, Cu, Si, Mg, Pt, Nd, Al, Sn, Fe. These eleven metals establish 97% of the total pure metal value of a single average smartphone, with Au already making up 72% of the total metal value, although metal content of Au is only 16.83 mg per device (0.0152% of total weight). Fe is the total most abundant metal in smartphones with an average weight of 15.98 g (14.82 wt-% of total device), yet only adds a small fraction of 0.8% to the total pure metal value. Metal content for the 7.42 billion devices sold in 2012–2017 and current pure metal value for these eleven metals is presented in Table 1.

In general, the recycling driving elements for WEEE are Au, Ag, Cu, Pd, and Pt, as they are relatively easy to recover by standard recycling processes in a typical copper melt via electrolysis (Reuter et al., 2013), and as they gain the most value. Yet, different recycling facilities use different technologies. Fig. 3 illustrates the metal value over the years 2012–2019 of the four metals Au, Cu, Pd, and Pt, based on their fractional content in a smartphone (averaged monthly prices). Ag is disregarded as the fractional metal value per single device is less than 0.01 US $. Au alone constitutes more than 80% of the sum metal value of

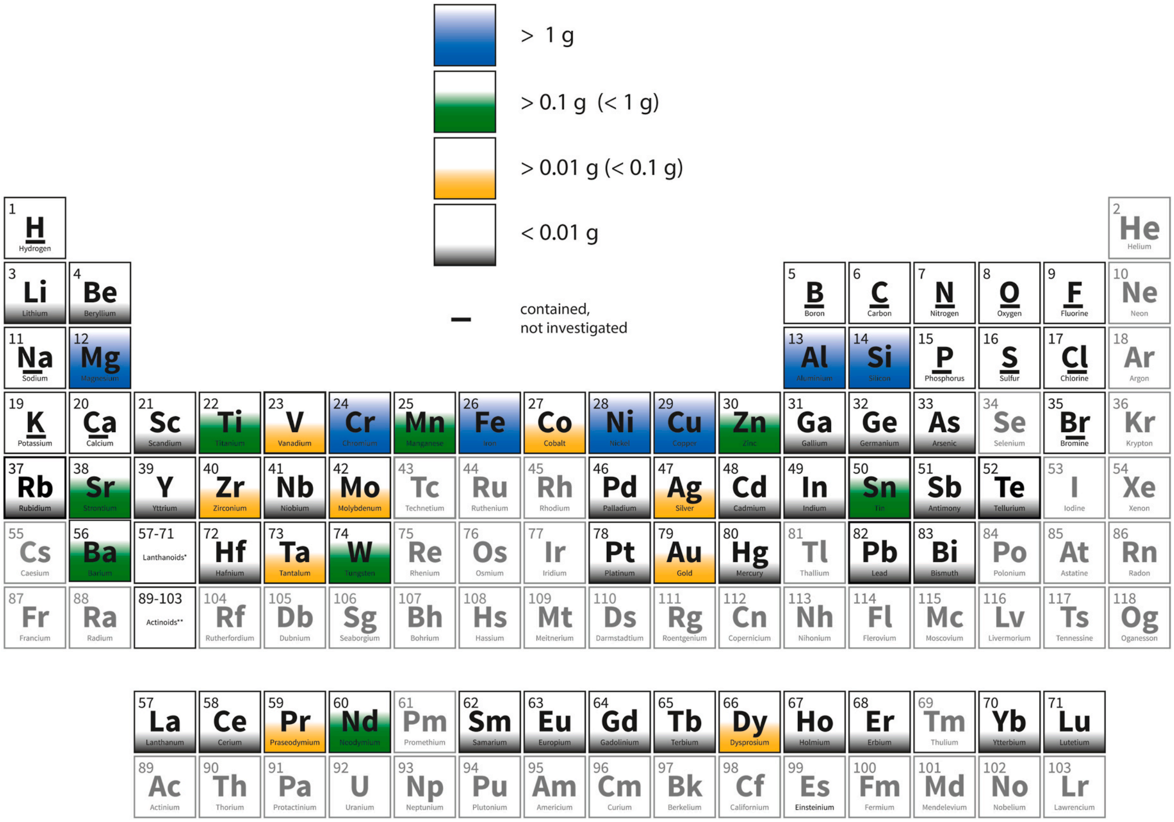

Fig. 1. *Investigated elements in selected smartphones and their average content.*

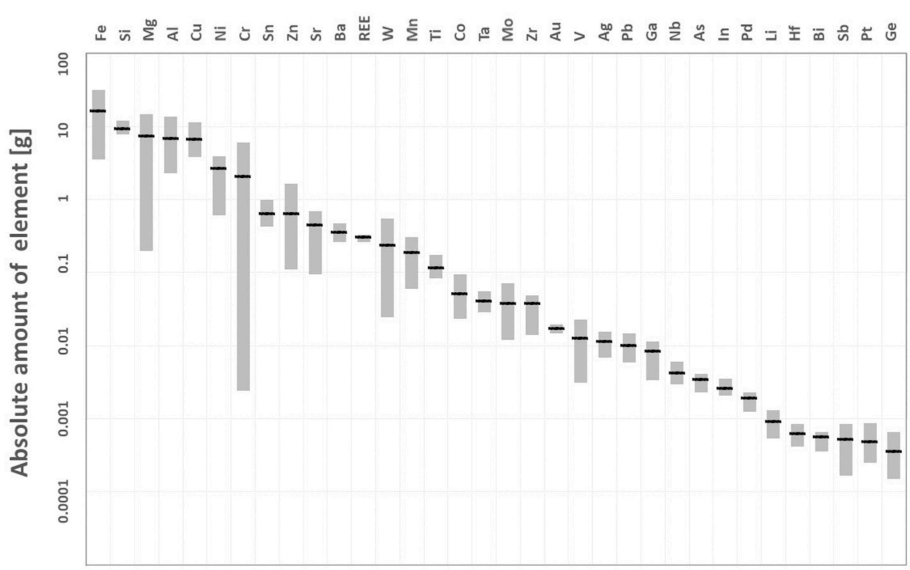

Fig. 2. Total measured metal content in smartphones in descending order. Black lines are mean measurements; grey shaded areas show the content range from the three investigated smartphones (minimum and maximum values). Rare Earths elements (Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu, Y) are combined and are shown here as REE. Note the logarithmic X scale.

these four metals (in the set timeframe ranging from 82 to 90%, with a value of 0.58–0.91 US $); the Pd fraction rose from 4% to 11% and adds now 0.09 US $ per device. Pt per device was worth between 0.01 and 0.03 US $; Cu between 0.03 and 0.06 US $.

Assuming a higher than 95% recovery for these four metals (Hagelüken, 2014), the sum in this figure can be seen as a rough estimate for the metal value of smartphones recoverable by standard recycling facilities. Potentially recovering 100% of these four metals would account for 84% of the total pure metal value of a smartphone device.

For better comparison, for selected metals their location (complete device vs pcb vs magnets) as well as their fractional pure metal value is given in Table 2. REE currently constitute only 2% of the total pure. metal value of a smartphone (0.03 US $), with Nd taking up more than half of that. When looking at the magnets alone, REE establish up to 96% of their metal value. The pure metal value for magnets was highest in 2012 with 0.06 US $ per single device.

Table 1
The eleven most valuable elements in smartphones, based on their fractional content and current value (Nov 2019 prices). Fractional metal content for 7.42 billion smartphone devices sold in 2012–2017 is calculated as well as current value in these 7.42 billion smartphones for each metal. Sorted by descending metal value.

Metal	Total content in 7.42 billion devices [t]	Value in 7.42 billion devices (11/2019) [US $]
Au	125	6,000,000,000
Pd	14	807,000,000
Ni	19,000	294,000,000
Cu	49,000	287,000,000
Si	69,000	164,000,000
Mg	54,000	119,000,000
Pt	4	103,000,000
Al	49,600	88,000,000
Nd	1600	82,000,000
Sn	4800	78,000,000
Fe	119,000	50,000,000

3.3. Selected metals: geological occurrence and comparison to smartphone content

Metals Au, Cu, Pd, Pt, and by-products Co, Ga, Ge, In, REE, and Ta were further investigated and selected data are listed in Table 3 (sorted alphabetically by chemical symbol). Crustal abundances and metal grades in source minerals from current mine production (see methods section for term definitions and references) are used as comparison for primary occurrence versus metal content in smartphones. To understand country concentration and their implications, the three main producing countries and their global production share is displayed, and their global production in tons to understand market size. For the time 2012–2017 with 7.42 billion sold smartphones, the content of each metal for 7.42 billion smartphones is calculated. The share which these metals would potentially have on global supply is also given. Note that this is mainly a comparison for primary resources, as mine data were used where possible instead of supply data.

Rare earth element mining data are only available as Rare Earth Oxides (REO); thus, shares are only estimated due to conversion from REE to REO. Mining data for REO is without estimated illegal production.

For selected metals Au, Cu, Pd, Pt, and by-products Co, Ga, Ge, In, REE, and Ta, their main current mine sites are plotted versus measured content in smartphones for comparison in Fig. 4.

Brief summaries for these selected metals about their geological occurrence, their grades in current mine sites, their recycling aspects, and their usage/content in smartphones is described in the **supplementary information**.

X-Axis: numbered mine sites in descending order of production capacity; s for total smartphone, pcb for printed circuit board, m for magnets.

Data from BGR and Co (Al Barazi, 2018); Cu (Mudd et al., 2013); Ga (Liedtke and Huy, 2018; Frenzel et al., 2015); Ge (Frenzel et al., 2015); In (Liedtke and Huy, 2018); REE (Van Gosen et al., 2017); Ta (Damm, 2018; Schulz et al., 2017a).

Pd, Pt: Mine sites no 1 (Pd) and no 7 (Pt) have low grades at ~ 0.3 mg/kg that are almost not visible in this figure.

4. Discussion

We have investigated the metal content of three top smartphone sellers from 2012, representative for smartphone generations released to the market from 2012 to 2017. There were many different models and brands developed during this time period, and examining all these models in the same way as we did with our three models would be a task inconceivable for any research. To date, public data for exact metal content of post 2010-smartphone generations are not published, apart from Holgersson et al. (2018). With a general life time of smartphones of 2–3 years, and an additional retention time of 2–3 years, whereby unused smartphones are often lying in consumers' drawers (Bookhagen et al., 2013), devices now reaching the recycling facilities are 5+ years

Table 2
Location, weight and metal content of smartphone components for value comparison; Nov 2019 prices.

	Average weight [g]	Total metal value [US $]	Content of selected metals [mg]	value of selected metals [US $]
complete smartphone	110.7644	1.13	Au 16.83	
			Cu 6606.41	} 0.95 US $
			Pd 1.91	
			Pt 0.48	
			REE 303.39	0.02 US $
pcb	15.7262	0.93	Au 15.13	
			Cu 6504.64	} 0.86 US $
			Pd 1.89	
			Pt 0.17	
			REE 10.59	<0.01 US $
magnets (total)	1.0311	0.02	Cu 0.93	<0.01 US $
			REE 292.01	0.02 US $

Fig. 3. The value of Au, Pd, Pt, and Cu based on their fractional content in smartphones, calculated over the timeframe 2012–2019. The top line represents the sum of their fractional values.

Table 3
Selected technology metals and their average content in Earth crust (I), in current mining production (II) and in smartphones (III); their top three production countries (IV), and their annual global mine production for 2016 (V); the quantity of each metal in smartphones in 7.42 billion smartphones sold from 2012 to 2017 (VI); their content in smartphones for this six year period as share of global primary supply in % (VII) and in days (VIII). (1): conventional mining data only, ASM (Au), illegal (REE) not included *refinery data (no mine data available).

	I	II	III	IV	V	VI	VII	VIII
	Average crustal content [mg/kg]	Range of metal grades in ores from mine production [mg/kg]	Average content in smartphone [mg/kg]	Top 3 mine producing countries 2016 and global production share [%]	global production (2016) [t]	content in smartphones sold in 2012–2017 [t]	Share of VI on V [%]	Share of VI on V in days
Gold (Au)	0.004	0.6–4.6 (1)	155	China 14, Russia 9, Australia 9	3222 (1)	125	3.88	14 days
Cobalt (Co)	25	1000–6000 (1)	496	DR Congo 58 Australia 6, Cuba 5	110,696 (1)	411	0.42	2 days
Copper (Cu)	60	3400–20,000 (aver 4900)	57,896	Chile 27, Peru 12, China 9	20,380,000	49,000	0.21	<1 day
Gallium (Ga)	18	Average 57; up to 120	82	*China 89, Ukraine 3, Russia 3	*282	70	24.82	91 days
Germanium (Ge)	1.6	30-279; up to 850	3	*China 79, Canada 15, Russia 6	*104	3	2.51	9 days
Indium (In)	0.049	25–50	23	*China 43, Rep Korea 30, Canada 10	*689	19	2.78	10 days
Palladium (Pd)	0.015	0.03–14.28	17	Russia 39, S-Africa 36, Canada 9	221	14	6.41	23 days
Platinum (Pt)	0.0005	0.03–19.2	5	S-Africa 70, Russia 11, Zimbabwe 8	192	4	1.84	7 days
REE (Rare Earth Elements)	0.3–63	300 -88,000 REE	2749 REE	*China 86, Australia 11, Russia 2	*127,400 (REO)(1)	2251 (REE)	Approx. 1.77	Approx. 6 days
Tantalum (Ta)	0.7–2	182-250 (1)	362	*DR Congo 41, Rwanda 19, Brazil 14	*1491 (1)	298	20.01	73 days

old (Oguchi et al., 2011); thus, this study presents relevant actual data. Once smartphones reach recycling facilities, this does not necessarily imply that recycling of all metals is economically feasible nor that it is ecologically reasonable (Reuter and van Schaik, 2012). On the one hand, each metal and its characteristics for recycling must be considered separately (price, grade, economic scarcity, and supply of the metal), but on the other hand these must be investigated in the context of total content in a complex matrix with thermodynamic boundaries, interfering chemistry and current standard technologies, to name a few aspects. This hypothesis is further explained with the example of Ta below.

The calculated pure metal value for all 53 metals has an average of 1.18 US $ per single smartphone over the years 2012–2017, but it shows highly volatile prices, with total metal value up to a high of 1.36 US $ in 2012. This becomes even more visible when looking at the major value driving elements Au, Pd, Pt, and Cu: Per single device, these four metals average from 1.07 US $ in 2012 to a low of 0.66 US $ in 2015 and a current value of 0.83 US $ (Nov 2019). Although Pd prices more than doubled over the past three years, this only leads to an increase in metal value of 0.03 US $ per device due to the low amount of Pd contained. Pd and Au content in measured smartphones is lower (0.017 g Au and 0.0019 g Pd) than in older mobile phones (0.024 g Au and 0.009 g Pd) (Hagelüken, 2014). E.g., Pd in multilayered ceramic capacitors has been replaced by alloys that contain much less Pd. The reduced use of precious metals, be it by new and improved materials, or miniaturization of components – all partly important steps to resource efficiency – could affect the economics of recycling materials from complex products, with less economically attractive metal value in terms of revenues, and the issue of profitability of low grade materials and dissipation (Reuter et al., 2013; Izatt, 2016). Economic exploitation requires collecting sufficient quantities of the distributed products (Izatt, 2016). The content of a single device does not provide an economic incentive for recycling, it is the vast number of smartphones that draws attention for possible metal recovery (Hagelüken, 2014).

When calculating the pure metal values for the 7.42 billion sold smartphone devices in the years 2012–2017, the relatively small amount of metals per single device adds up to more impressive numbers; with Nov 2019 prices, the total metal value from these smartphones is at 8.4 billion US $. With gold accounting for 72% of the pure metal value alone, current recycling methods from an economical viewpoint are perceptible. Au, Pt, Pd and Cu are recovered in established standard recycling processes because these four metals have much higher content in smartphones than in primary ores.

Au, Cu, Pd, Pt constitute only 12 wt-% of the investigated 53 metals, which totals to 6 wt-% of the complete device. Yet these four metals contain 84% of the total 53 measured pure metals value and are the main recycling driving elements. Thus, current recycling technology mostly focuses on economic viability rather than on certain (rare) metal recycling, as already stated by Friege (2012).

Although Ga constitutes for only 0.1% of the value of the single smartphone device, the volume of Ga in smartphones (2012–2017) is about 25% of the annual production rate in 2016 (282 t Ga). For Ta, the value of the single device with 0.9% of the total value seems low, yet the Ta in smartphones (2012–2017) accounts for 20% of the annual global production for 2016 (1491 t Ta). In small markets such as Ga and Ta, effective EoL-recycling could significantly contribute to global production and could help lower the price volatilities. Discussions about availability and supply risks of metals is not a topic of this study; yet, especially for the smaller markets of minor metals and by-products such Ga, Ge, In, which are solely dependent on their host metal, comparison to ore grades in reserves are only a small indication for broad availability. This does not allow predictions for future supply; for supply scenarios, supply potentials including economic conditions and existing technologies, as stated by Frenzel et al., 2015, need to be considered. Ga and Ta also have a so called high country concentration of production: they have a high Herfindahl Hirschmann Index (HHI). The HHI score refers to a measure of market concentration and is an indicator of the amount of competition, i.e. if a market is highly concentrated and close to monopoly or if its diversified and competitive. Ga has a high HHI of 7890 and Ta of 2365 with few companies in few countries dominating production (DERA, 2019).

The display of technical devices is often termed as the In carrier in smartphones. ITO (indium-tin-oxide) is a semiconducting compound used in flat-panel displays. Yet, measurements of In in this study showed that concentrations on the pcb, where In is used in soldering and fusing, are even higher than in the display. For both components, In concentrations are partly higher than in primary ores. Yet for smartphones, In recycling from displays is not feasible due to complex built of the display and due to the small total amount (0.0004 g total per device). For

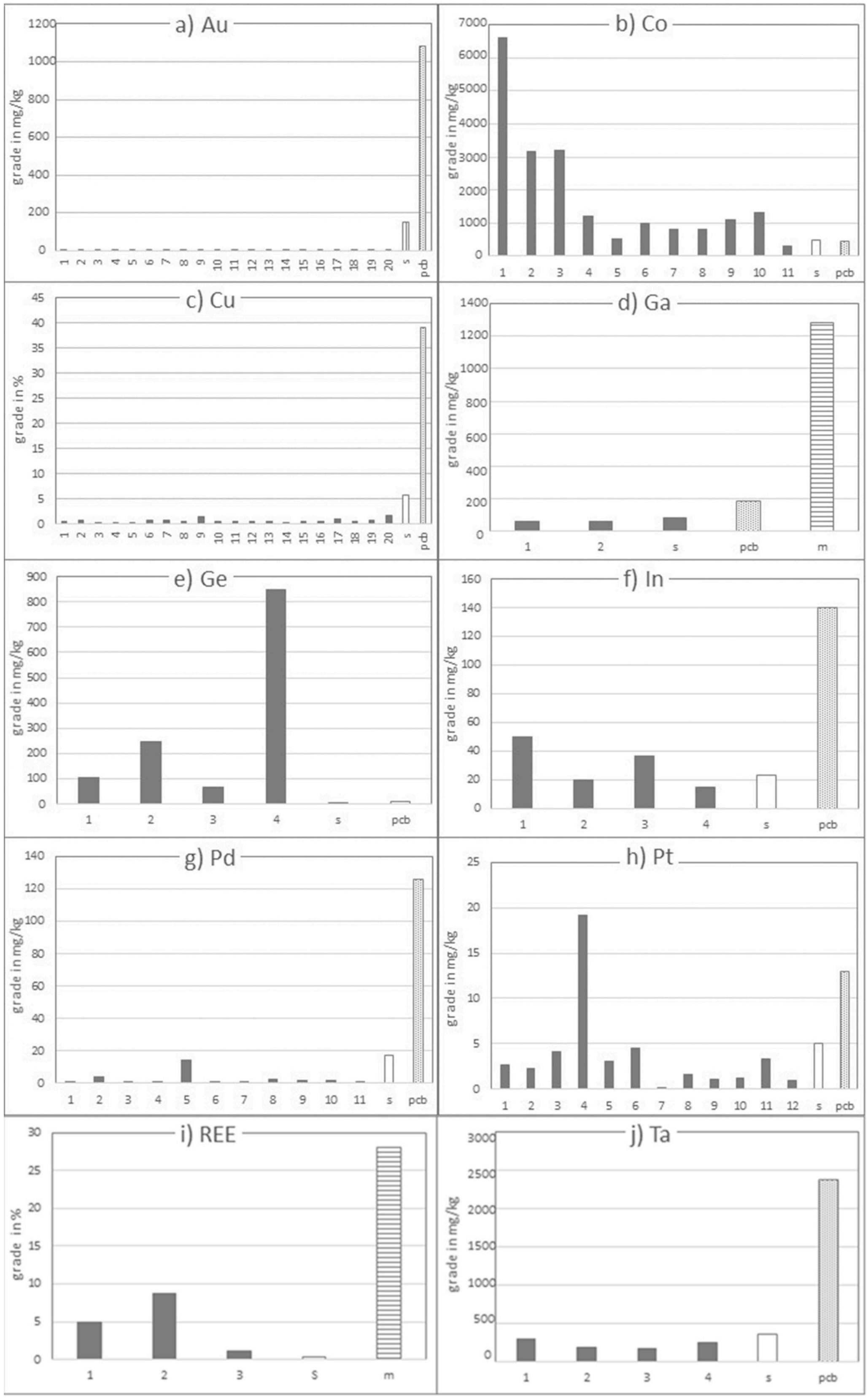

Fig. 4. Plots of metal content of currently (2016 data) mined primary ores in comparison to measured metal content in smartphones for **a) Gold** (20 largest mine sites, covering ~20% of global Au-production), **b) Cobalt** (covering 74% of LSM), **c) Copper** (20 largest mine sites, covering 40% of global Cu-production), **d) Gallium, e) Germanium**, **f) Indium**, **g) Palladium** (11 largest mines sites, covering 77% of global Pd-production), **h) Platinum** (12 largest mines sites, covering 79% of global Pt-production), **i) Rare Earth Elements** (covering 65% of global mine production), **j) Tantalum** (covering 60% of conventional mining). For by-products Ga, Ge, In, data are a summary of estimated grades.

comparison, for Ga and In from photovoltaic (PV) panels, EoL recycling is even expected to remain more costly than primary production (Redlinger et al., 2015). With PVs containing more total In than smartphone displays due to size, contributions to In supply from smartphone display recycling remain doubtful. The pcb however could be a future target, depending on the feasibility of recycling these complex compounds with yet low total In content (on average 0.0022 g In per pcb). Extraction of In from pcb is partly economic and is facilitated in one known plant with a recovery of approximately 50%.

REE in displays are present only in very low quantities, far lower than in primary ores; recycling of REE from smartphone displays does not seem feasible.

The Co content in pcbs is below the Co content in currently mined ores, and due to the complex built of pcbs recycling of Co does not show a clear advantage. However, Co in batteries (not investigated in this study) still remains an important factor (Al Barazi, 2018), and recycling infrastructures for lithium-ion-batteries already exist (Harper et al., 2019).

Especially for REE, the recycling advantage of magnets from loudspeaker, camera and vibration motor is clearly visible (see also Table 4), and permanent magnets have already been termed as the most valuable waste streams for REE (e.g., Jowitt et al., 2017). Yet, REE recycling regarding magnets mainly focuses on recovery from permanent magnet production processes and reasons for this have been summarized by Reimer et al., 2018. Processes for EoL-recovery from smartphones are still mostly in preliminary or smaller non-industrial stages due to the design of smartphones (L. Ansorge, private communication). Additionally, Ga content in magnets is even higher than Ga in pcbs (see Table 4), and recycling of Ga from magnets could become a potential future target, once collection and separation of magnets have reached higher quantities. One company has developed a sorting machine that is able to completely separate a smartphone and thus the magnets, yet this only works for one smartphone model at a time. With new smartphones produced from 2018 and containing up to three cameras, total REE content per device is expected to be higher than in the investigated models.

Integrated smelters and refiners seem to be crucial for the treatment of WEEE from a recovery viewpoint, as they recover more than just the usual Au, Ag, Pt, and Pd – yet, collection and transport of EoL-products as well establishing new facilities and other technologies also need to be considered. Extracting small amounts from complex matrices is thermodynamically not always feasible and studies point to the fact that 100% recycling is often not ecologically sound (Reuter and van Schaik, 2012). Also, Reuter et al. (2019) suggests that Pb–Zn–Cu as the carrier matrix need to remain part of devices to facilitate recycling in Europe; Pb has been the target of EU-wide bans in materials since the RoHS directive (Restriction of Hazardous Substances, EU Commission, 2011).

Currently, recycling of smartphones (as shown above) is economically driven by precious metals and copper. Generally, legislative recycling rates are mass-based (Friege, 2012; Huisman et al., 2007). Yet, in contrast to their relative weight, recycling of precious and speciality metals could have larger environmental benefits (Wäger et al., 2011). To facilitate a circular economy as proposed by the European commission (EU Commission, 2020), or the Ellen McArthur Foundation (2013), where each metal matters, different approaches than the current mass-based or economically driven approach might be required for the future. These new approaches might not always be the most economically options, but could consider environmental, social and resources aspects as well. As mentioned before, 100% recycling is not ecologically feasible (Reuter and van Schaik, 2012). A holistic approach, defining which metals are important, why and how they need to be targeted, is required. Combining circular economy and criticality is a rather new aspect, and has been further discussed by Gaustard et al. (2018). Our data can provide necessary background information helping to decide about the significance of metals.

Table 4
Concentration of selected metals in smartphones as a factor in comparison to current mine sites (for by-products Ga, In, REE in host ores). E.g., Au in the complete device has a concentration 34 times that of rich primary gold ores, Au on the pcb is 234 times higher concentrated than in rich primary ores.

Metal	Average content in smartphone, complete device; factor compared to current mine sites	Average content in smartphone, pcb only; factor compared to current mine sites	Average content in smartphone, magnets only; factor compared to current mine sites
Au	34	234	–
Cu	3	22	–
Ga	–	3	16
In	–	3	–
Pd	–	9	–
REE	–	–	3
Ta	–	8	–

Thermodynamics are another key factor in regards to the circular economy concept (see Reuter et al., 2013; Reuter et al., 2019). For example, pcb, including those from desktop computer and laptops, are the main focus of most recycling and separation technologies for WEEE (Reuter et al., 2013). Current recycling processes for pcb are based on pyrometallurgical approaches focusing on the recovery of Cu and the precious metals Au, Pd, Pt, Ag, with integrated processes allowing the recovery of additional elements such as Pb, As, In, Te, etc. (Reuter and van Schaik, 2012; Hagelüken, 2014; Ueberschaar et al., 2017). With these processes, Ta ends up in the slag, where it is oxidized. Due to low Ta grades in the slag, recovery is hindered by high energy demands and high costs (Ueberschaar et al., 2017). To recover more Ta from consumer products, additional presorting and separation paths of the electronics would be necessary (Graedel et al., 2011). Yet, the small total amounts of Ta need to be weighed against required energy and further (pre-)processing. Thus, our data oppose common media outlets, which claim that smartphones should be collected for the recycling of Ta. Under current circumstances, with low total and dissipative content of Ta in smartphones and the difficulty of separation, with current technology and energy requirements as well as Ta prices, recovery of Ta from smartphones is not feasible.

To estimate a theoretical requirement of ores to produce a smartphone, we calculated the ore weight for each metal based on fractional metal content in the devices. For by-products such as Co, Ga, Ge, In, ore weight was calculated according to host (main) ore; e.g., the In fractional content is already covered by the Cu and Sn-fractional content, of which In is mined as by-product. A smartphone weighing on average 110 g requires at least 4.7 kg (higher grade ores) up to 138.7 kg (lower grade ores) of ores to produce all 53 metals for manufacturing a single smartphone. Four metals and their respective fractional content in ores account for over 90 wt-% of these 138.7 kg, when lower grade ores are used: Au (42 wt-%), Pd (28 wt-%), Pt (12 wt-%) and REE (9 wt-%). Note that this is merely a weight calculation based on metal content in ores; it cannot necessarily be used as an indicator for e.g. CO_2-usage or energy requirement because these vary depending on the extraction process for each metal, ore deposit and host rock. Yet, as stated in Nelen et al. (2014), the suggestion that the recovery of precious metals such as gold and palladium from an environmental point of view should be prioritized over mass-related aspects for recycling seems visible with these numbers and might be extendable for REE.

5. Conclusions

In this study, we determined the total amount of 53 metals in smartphones (exemplary for WEEE), provided background data about their primary production (production amount, prices, geological occurrence) and compared the metal content in smartphones with the metal content in primary ores. We discussed the reasons why for some of these metals, recycling currently seems to be feasible and for some not.

Especially mineral raw materials with a low overall annual production rate (i.e., around or less than 1000 metric tons such as Pd, Pt, Ga, Ge, In, and Ta) and with a high-country concentration of production (high HHI) can be affected by price- and supply risks. These elements together with other important elements for key future technologies such as Cu, Co, REE were investigated to provide facts for their recycling potential.

The current recycling of smartphones shows that with Au, Pd, Pt, and Cu, 82% of the pure metal value is successfully recycled. Due to the material dispersion, low total content and difficulties in separating components, recycling from smartphones at EOL is not yet economically feasible for Co (disregarding batteries), Ga, Ge, In, Ta, and the REE. Magnets from loudspeaker, camera and vibration motors are an exception and could be of interest for REE recycling, yet these small magnets need to be separated before processing. Given the current global market situation, Ga from magnets rather than pcb, and In from pcb rather than displays, could be of interest for future recycling. Due to the complex processes and different aspects regarding recycling, higher metal grades in smartphones do not necessarily implicate that recycling is economically or ecologically efficient. Yet, exact location and detailed content of metals in smartphones as investigated in our study can help foster the discussions on the effectiveness of circular economy, specifically regarding topics such as design for recycling, and recycling of complex matrices with interfering content.

For the future-oriented agenda of the EU Green Deal (EU Commission, 2020), a profound dataset is needed to investigate the upcoming metal demand and supply from secondary resources, required for a transition to a circular economy.

Our approach is a first step to contribute to this dataset, giving background specifics on selected metals from one future waste-stream. With our dataset, we also aim to contribute to the circularity discussion by accumulating detailed data for comparison of primary metals in ores with metals in a widely-used application. Our data point to further questions that circularity will be faced with: Which interaction of regulatory frameworks and economic incentives can strengthen recycling, including fully integrating ecological standards, social behavior, and technical feasibility? Ultimately, as 100% recycling of all metals in smartphones is not possible, the decisive task lies in the identification of the most relevant metals for recycling. Unquestionably, the transition to a circular economy includes a much larger complicated framework, integrating many more factors that we have not addressed here and that might prevail (see EU Commission, 2020).

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CRediT authorship contribution statement

B. Bookhagen: Conceptualization, Methodology, Data curation, Investigation, Writing - original draft. **D. Bastian:** Data curation. **P. Buchholz:** Writing - review & editing. **M. Faulstich:** Writing - review & editing. **C. Opper:** Data curation, Methodology. **J. Irrgeher:** Validation, Writing - review & editing, Supervision. **T. Prohaska:** Validation, Writing - review & editing, Supervision. **C. Koeberl:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2020.101750.

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