DISSERTATION / DOCTORAL THESIS

Titel der Dissertation /Title of the Doctoral Thesis

„Metallic Resources in Smartphones“

verfasst von / submitted by

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angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Doktorin der Naturwissenschaften (Dr. rer. nat)

Wien, 2020 / Vienna 2020

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	UA 791 426
Dissertationsgebiet lt. Studienblatt / field of study as it appears on the student record sheet:	Erdwissenschaften
Betreut von / Supervisor:	Univ.-Prof. Dr. Christian Köberl Univ.-Prof. Dr. Thomas Prohaska Dr. Johanna Irrgeher
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Preface

This thesis combines analytical studies of metallic resources for smartphones and geoscientific implications of the results. It was carried out at the Department of Lithospheric Research at the University of Vienna and at the Department of Chemistry at the University of Natural Resources and Life Sciences (BOKU), Vienna.

The PhD thesis is divided into three parts: 1) The development and analytical investigation of over 50 metallic elements of complete smartphones devices; 2) the transfer and application of the compositional information and their geo-economic implications with focus on geologic occurrence, supply, demand, and recycling of metallic resources; and 3) a complementary educational outreach study to implement the socio-ecological aspects of the topic and to include consumers on appropriate management for resource conservation.

The work is divided into 11 chapters, starting in chapter 1 with a general introduction of the importance and the far-reaching aspects of smartphones and their metallic resources for our society. A description of the laboratory work and development of the analytical method for qualification and quantification of metallic elements in smartphones follows in chapter 2, summarized by the concluding methodological publication in chapter 3. The significance of metallic resources in smartphones and their importance for sustainability and recycling is put into context in chapter 4. This application is concluded with the geo-economic publication in chapter 5. Chapter 6 initiates and describes the importance of the accompanying socio-educational outreach study, which results in the theoretical research on consumer behaviour for recycling (chapter 7), and in the creation of a comprehensive teaching material for schools and museums, finalized by the educational publication in chapter 8. The recapitulation of the thesis and its methods is provided in chapter 9. In chapter 10, a complete list of publications follows, and Chapter 1 lists additional non-reviewed work published by the author.

The results of the method development and analytical investigation have been published in the peer-reviewed journal *Analytical Methods* (chapter 3).

The results of the investigation of smartphones and their impact on geo-economic factors have been published in the peer-reviewed journal *Resources Policy* (chapter 5).

The peer-reviewed *Journal of Geoscience Education* has published the results of the outreach study (chapter 7).

Summary

Our modern society heavily depends on metallic elements and their reliable, sustainable supply to meet our growing demand and to sustain our current lifestyle. Increasingly complex technologies have contributed to an increase in both the number and supply of specific metallic elements needed to manufacture these devices. The key in understanding which raw materials can be utilized in future energy systems lies in estimating the availability of these materials through quantitative assessments and predictions. This study aims at placing smartphones in its geoscientific context by identifying the metallic content in smartphones and its potential to increase the availability of specific metallic elements through recycling.

Smartphones are continuously cited for containing many different strategic metallic elements, and they are mentioned in discussions about future supply and criticality of metals, as well as for metal stocks of the urban mine for potential recycling solutions. Smartphones are also frequently discussed in the context of sustainable sourcing, conflict minerals, and potential circular economy concepts. With high sale numbers of 1.4 billion devices sold each year yet very low recycling rates, smartphones seem to be the prime example to combine today's sustainability issues with everyone's concern.

In spite of their importance, data for newer smartphone generations are still missing, and no detailed values for metallic content are publicly available.

This thesis combines the development of an analytical method to quantify 53 metallic elements in smartphones and the thorough investigation of the metals' geoscientific importance with focus on occurrence, production, demand, supply, recycling, and sustainability. Additionally, the impact of smartphones on commodity markets and potential availability of metallic elements is investigated.

The elemental composition of complete smartphones is facilitated both qualitatively and quantitatively using mass spectrometry and optical emission spectrometry. The results are used to document the raw material demand for the production of these types of smartphones. This allows to generate a product-specific database for smartphones and their mineral resources with a main focus on metallic elements: their geological occurrence and economic importance (production rates and countries), their metal stocks to discuss potential supply risks, criticality, and recycling, as well as possible circularity concepts.

The general public often does not connect geologic occurrence and mining of the metallic elements with smartphones. This vastly underestimates the importance of geoscientific investigations and their applications to provide for society's wellbeing. This study aims to close this knowledge gap and combines geoscientific results with a field study in modern translational research for development of an educational module.

Zusammenfassung

Die moderne Gesellschaft ist von einer zuverlässigen, nachhaltigen Versorgung mit metallischen Elementen abhängig um die wachsende Nachfrage zu bedienen und unseren gegenwärtigen Lebensstil aufrechtzuerhalten. Insbesondere für Hightech-Produkte und zukünftige CO_2-arme Technologien wird eine breite Palette von speziellen Metallelementen benötigt. Der Schlüssel zum Verständnis, welche Rohstoffe in zukünftigen Energiesystemen verwendet werden können, liegt in der Abschätzung der Verfügbarkeit dieser Materialien durch quantitative Bewertungen und Vorhersagen. Diese Studie zielt darauf ab Smartphones in ihren geowissenschaftlichen Kontext zu stellen, indem der Rohstoffgehalt in Smartphones und dessen Potenzial zur Erhöhung der Verfügbarkeit bestimmter Metalle durch Recycling ermittelt werden.

Smartphones werden häufig für ihre verschiedenen strategischen Metallelemente zitiert: Bei Themen der zukünftigen Versorgung und Kritikalität von Metallen, bei Metallvorräten der „urbanen Mine“ für potenzielle Recyclinglösungen, bei nachhaltiger Beschaffung oder Konfliktmineralien und bei möglichen Konzepten der Kreislaufwirtschaft. Mit einer hohen Anzahl von 1,4 Milliarden verkauften Geräten pro Jahr, aber einer sehr niedrigen Recyclingrate scheinen Smartphones das beste Beispiel zu sein, um die heutigen Nachhaltigkeitsprobleme mit verschiedenen Aspekten zu verbinden.

Trotz ihrer Bedeutung existieren keine Daten neuerer Smartphone-Generationen und es sind keine detaillierten Angaben über ihre Metallinhalte verfügbar.

Diese Arbeit kombiniert die Entwicklung einer Analysemethode zur Quantifizierung von 53 metallischen Elementen in Smartphones mit einer Untersuchung der geowissenschaftlichen Bedeutung der Metalle in Bezug auf Vorkommen, Produktion, Nachfrage, Angebot, Recycling und Nachhaltigkeit. Letztendlich werden die Auswirkungen von Smartphones auf die Rohstoffmärkte und die potenzielle Verfügbarkeit metallischer Elemente untersucht.

Die Elementzusammensetzung kompletter Smartphones wird sowohl qualitativ als auch quantitativ mittels Massenspektrometrie und optischer Emissionsspektrometrie detailliert ermittelt. Mit diesen Ergebnissen lässt sich der Rohstoffbedarf für die Herstellung der Smartphones untersuchen. Dies ermöglicht die Erstellung einer produktspezifischen Datenbank für Smartphones in Bezug auf deren metallische Rohstoffe. Diese Daten werden für die Diskussion speziell für die Untersuchung der geologischen Vorkommen, der wirtschaftlichen Bedeutung (Produktionsraten und Länder), der Metallvorräte für potenzielle Versorgungsrisiken, Kritikalität und Recycling, sowie für mögliche Ansätze für zukünftige Kreislaufwirtschaftskonzepte verwendet.

In unserer Gesellschaft wird der Zusammenhang von Geowissenschaften und Smartphones normalerweise nicht erkannt. Generell wird die Bedeutung geowissenschaftlicher Anwendungen von der heutigen Gesellschaft nicht wahrgenommen. Für eine Sensibilisierung dieser Themen in Schulen kombiniert diese Studie moderne translationale Forschung mit der Entwicklung eines Outreach-Moduls über Smartphones.

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1. Introduction: Motivation for investigating smartphones

The general public often does not connect between geologic resources and their daily life, as the link to Earth and its resources is not obvious. However, Earth science is a key component in shaping policies that appropriately weigh the importance of resource conservation, use, and sustainability (Feinstein & Kirchgasler, 2015). Modern geosciences - in addition to fundamental research questions - also include new approaches and concepts to address societal needs and concerns, for example the urban mine concept and the circular economy concept. Modern geosciences will help society to understand and make environmentally sound decisions (Locke, Libarkin & Chang, 2012; EU Commission, 2020). In the past, the analysis of primary resources from mining and secondary resources from recycling have been mostly investigated separately to address the need for raw materials. However, in order to support our supply and to interpolate our demand, it is imperative to consider and investigate both types of resources (DERA, 2019). Global resource management has developed into a multifaceted and highly interdisciplinary scientific task: Several geological, metallurgical and other raw material sciences are needed to investigate supply of metallic elements from mining and recycling. Recycling is partly regulated by legislators and partly driven by economic factors, which means it is also very dependent on producers (e.g., by material and design) and consumers (e.g., by returning used devices to the recycling chain; Huisman et al., 2017; DERA, 2019; EU Commission, 2020). Hence, when discussing our resource needs including recycling, geosciences and material sciences need to be combined with economic, ecologic and social sciences to appropriately address the topic.

The research in this PhD thesis focuses on smartphones - a device that everyone can relate to. The study addresses future metallic element demand for smartphones, smartphones' impact on annual metal production, the current status and future potentials for recycling from smartphones, and thus eventually the potential availability of metals for other technologies.

There are several reasons why smartphones are of interest and have become a symbol of our current generation: A high-tech status symbol with vast sale numbers of over 1.4 billion devices annually, smartphones are an almost ubiquitous device that have – for the most part – made societies life more comfortable (Siewiorek, 2012; Statista, 2019). Yet, the multi-metal content, low recycling rates, intransparent value chains with partly dire labor conditions and ecological impacts for some of the raw materials have caught the public eye, and smartphones with their short usage times have become one prime example for unsustainability (Reuter et al., 2013; Nordmann et al., 2014; Huisman et al., 2017; EU Commission, 2020). Smartphones (among other products) are continuously mentioned in discussions about future supply and criticality of metals, and for metal stocks of urban mines for potential recycling solutions (e.g., Reuter et al, 2013; Huisman et al., 2017). Smartphones are frequently cited when discussing sustainable sourcing and conflict minerals, e.g., in connection with tantalum and cobalt (Amnesty International, 2016; European Parliament, 2017). Circular economy concepts and the UN's Sustainable Development Goals provide a larger background in which mobile phones and specifically smartphones are often stated as prime example for potential new transition models (Ellen McArthur Foundation, 2013; EU Commission, 2020; UN, 2015).

In this introductory chapter, several interdisciplinary aspects will be identified in an overview, and main aspects will be investigated in the following chapters in more detail.

To set a foundation to capturing the impact of smartphones on consumer markets and raw material consumption, the brief history about the rise of smartphones to their current high sale numbers is described in the following section.

1.1. Smartphones: Definition and market prominence

Smartphones are a class of mobile phones equipped with specific functions. There is no single definition of a smartphone, but the general functions of smartphones allow to distinguish them from common mobile phones (so called feature phones): an operating system can be installed that runs third-party applications, and they possess multimedia functionality for playing music, videos and taking pictures, and wireless connectivity to the internet (Gartner, 2012). A touch display replacing the keypad and a larger screen for smartphones are the key visual distinctions between the phone types.

The first mobile phones have been around since the 1970s. The first recorded mobile phone call took place in 1973, when a senior engineer at Motorola called a rival telecommunication company and informed them he was speaking via a mobile phone. The first commercial mobile phone is usually identified as the Motorola DynaTAC 8000X, launched in 1983 with a price of almost 4000 US $. Most of the early mobile phones were installed in cars due to their heavy and large units (KnowYourMobile, 2020). In the 1990s, mobile phones became available for the average customer, with affordable and portable designs starting the global rise of mobile phones. Unit sales rose at the beginning of the 2000s, passing the 1 billion sales mark in 2006 (Gartner, 2012).

The technology of early mobile phones compared to today was simple and primary use of the devices was dedicated to voice communication. The first device to combine telephonic functions and organizing functions (then called a personal digital assistant) was the Simon Personal Communicator by IBM, which appeared in 1993 and was sold approx. 50,000 times; it is identified as the first commercial smartphone and already features a touch screen (Bloomberg, 2012).

Commercial smartphones became more broadly available starting 2007, with 120 million units sold by different companies and marking the rise of smartphones (Gartner 2012). In 2013, smartphone sales passed the 1 billion sales mark, now overtaking the mobile phone market (with 1.02 billion smartphones out of 1.8 billion total sold mobile phones). In 2019, of 1.8 billion mobile phones, 1.37 billion were smartphones, a slight decline compared to the four previous years, where smartphones sales already reached over 1.4 billion sales. In spite of the small decline of smartphones sales from 1.40 billion (2018) to 1.37 billion units (2019), which reflects the slightly lengthening lifespan of devices, a slight saturation and a perceived lack of innovation within the market (Gartner, 2020), the high sale numbers presented here still depict the importance and popularity of smartphones. Yet, the current Covid-19-pandemic has also affected smartphones sales (IDC, 2020).

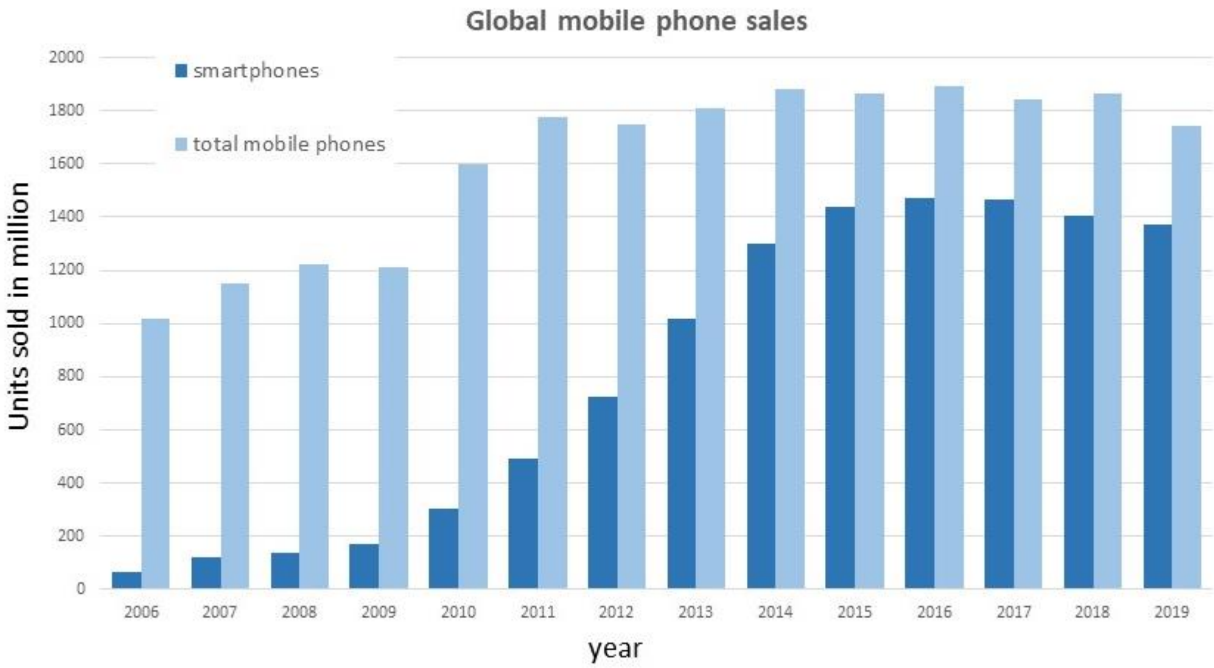

Figure 1.1*: total mobile phones and smartphone sales for 2006 – 2019 (Gartner, 2012; Gartner 2020; IDC, 2020).*

Summarizing, from 2007 until 2019, in total 21.60 billion mobile phones units were sold, of which 11.43 billion units were smartphones (Statista, 2020a), see **Figure 1.1**.

Smartphone coverage is also rising in emerging countries, and, e.g., the African Countries Ghana, Kenya, and Nigeria already show that around 30 % of adults in 2017 own a smartphone, with another 45-48 % possessing a mobile phone that is not a smartphone, as compared to smartphone ownership of 77 % in the USA and 72 % in

Germany, plus 17 % and 22 % respectively owning a mobile phone that is not a smartphone (Pew Research Center, 2018). The global median (2017) is at 59 % of adults owning a smartphone, subdivided into sub-Saharan Africa (median of 33 % of adults reported owning a smartphone), while Asia-Pacific (53 %) and Latin America (54 %) are closer to Europe (70 %) in median smartphone ownership. A large rising market is seen in India, where in 2017, 22 % own a smartphone, 56 % own a mobile phone that is not a smartphone, and 26 % own no mobile phone (Pew Research Center, 2018). In poorer countries, smartphones can be extremely important tools where robust internet access and static use is not as widespread, and given the globally rising middle class, smartphone sale numbers are expected to grow again after the pandemic (Pew Research Center, 2018; Statista, 2020a).

1.2. Smartphones and sustainability

Smartphones have been symbolized by many initiatives that address sustainability issues. Sustainability remains an open concept, but most definitions encompass generally three pillars: economic, social, and environmental aspects (e.g., Purvis et al., 2019). Due to the clear raw material focus of this thesis, this discussion will concentrate on sustainability aspects addressing raw materials. Owing to the fact that almost everyone in the western world possesses a smartphone (ITU, 2020), these devices can be used exemplary for many issues otherwise invisible to consumers; it can help individuals identify with raw materials issues which would otherwise feel distant and unrelated (EU Commission, 2020a).

This study investigates smartphones as representative for consumer electronics, also called ICT devices (Information and communication technology). Mobile phones, laptops, tablets, netbooks, notebooks and the like have very similar metal contents (Reuter et al., 2013). With high sale numbers over the past years, numerous of these ICT devices will reach or have reached their end-of-life (EOL), yet recycling rates have been and continue to be desolately low (Graedel et al., 2011; Huisman et al., 2017). Of ICT devices, smartphone sale numbers are by far the highest (see previous section). On the one hand, smartphones can have a positive impact on resource use, as they pool many features in one device, combining a music player, a camera, and a telephone, for example. Yet, the sheer number of sold devices rebounds these advantages and counteracts by increasing overall consumption (Makov & Vivanco, 2018). Smartphones and ICT are part of waste electrical and electronical equipment (WEEE), which is a waste stream of high importance for European circular economy projects (the so-called EU Green deal; EU Commission 2020a), see **chapter 4.2**. This is partly due to their multi-metal content, the low recycling rates, and high consumer involvement regarding purchasing and recycling (see **chapter 6**). The production of electrical and electronic equipment (EEE) is one of the fastest growing markets in the world, which also means that the amount of WEEE will continue to increase in the coming decades (OECD 2019; EU Commission, 2020): WEEE is already the world`s fastest growing waste stream (Forti et al., 2020). The amount of WEEE (in the USA also termed e-waste) globally has increased by 21 % in the last five years. Yet, only 17.4 % of WEEE was collected and recycled globally in 2019. This leaves 82.6 % unaccounted for (Forti et al., 2020). This also stresses the importance of waste management and waste return patterns, which depends to some extent on consumer behaviour, addressed in **chapter 7**.

Other factors that stem with ICT and smartphones in terms of sustainability have advanced continuously: Toxic content in early mobile phones and issues regarding the management of waste have been significantly dealt with by EU directives since the early 2000s (see chapter **1.2.1**). Additionally, in the past decade, sustainability aspects and transparency along the value chain by addressing the social and environmental issues of the complete life cycle have become more and more important for producers and consumers. Companies are challenged to provide information where their materials come from and where these materials end up, which also incorporates the concept of extended producer responsibility (EPR) (Davis, 1998). This especially includes raw material extraction and production stages at the beginning of the life cycle, where media attention for possible negative effects of production (such as child labor, see **Figure 1.2**) and conflict minerals play an increasingly important role (e.g., Enough Project, 2009; Poulsen, 2010; Amnesty International, 2016). EPR also encompasses recycling at the end of the life cycle, which was well illustrated already by the Unicef Photo of the Year in 2011 (**Figure 1.3**): a boy stands on a pile of electronic waste in a dump near Ghana's capital Accra (UNICEF, 2011). The importance and public attention has not declined since, as can be seen in the 2018 documentary “Welcome to Sodom” (Weigensamer & Krönes, 2018). In 2019, still around 7-20 % of the total

***Figure 1.2**: Child labor as one of the many issues at the raw material extraction.*

***Figure 1.3:** UNICEF Photo of the year 2011, showing the waste pile of Agbogbloshie in Ghana.*

WEEE are estimated to be exported as second-hand products or (illegal) WEEE (Forti et al., 2020). These issues, addressing social, sustainability and transparency aspects along the value chain specifically on both ends, raw material extraction and recycling, will be discussed in detail in **chapter 4.3**, along with the regulatory directives affecting the origination of raw materials. The overall sustainability frame is set by the circular economy concepts and the Sustainable Development Goals of the United Nations, described in **chapter 4.2**. The importance of consumers in terms of purchasing behavior and sustainable resource use is addressed in **chapters 6** and **8**.

A brief overview of European legislations and directives directly affecting mobile phones, their metal content, and their recycling will be given in the following section to provide the legal boundary conditions.

1.2.1. Brief overview of EU-directives directly affecting ICT and mobile phones

ICT in general and mobile phones in specific are mainly affected by three EU directives, dealing with the content of products (REACH and RoHS) and their recycling (WEEE). These directives started to evolve in the late 1990s and in the early 2000s and are European efforts to reduce hazardous materials in electronics; they were already partly motivated to address the global issue of growing consumer electronics waste.

REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) defines procedures evaluating information on the properties and hazards of substances. Companies have to register all substances used in their products and must show how the substance can be used safely and provide users with information on risk management measures. REACH (1907/2006/EC) came into force in June 2007 and is implemented by the European Chemical Agency (ECHA) (European Commission, 2019a).

RoHS (Restriction of hazardous substances) restricts the use of hazardous materials found in electrical and electronic equipment (EEE). RoHS 1 (2002/95/EC) was adopted in 2003 and to be enforced in 2006, and since RoHS 2 in 2011 (2011/65/EU), all electronic devices in the EU market require CE compliance, clearly visible with the CE mark on products. It also made non-compliance a criminal offence subject to fines. With the latest RoHS recast in 2019 (RoHS 3: EU Directive 2015/863), 10 substances are restricted and must conform within a restricted content: cadmium, lead, mercury, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl ethers, and four different phthalates (DEHP, BBP, BBP, DIBP). RoHS compliance testing is facilitated by probing of samples, usually with X-ray fluorescence or XRF metal analyzers and a detailed documentation such as the bill of materials (European Commission, 2019b).

WEEE (Waste electrical and electronical equipment; Directive 2002/96/EC, recast Directive 2012/19/EU) mandates the treatment, recovery and recycling of electric and electronic equipment. The first WEEE was adopted in 2003 and set collection, recycling and recovery targets for electrical goods. The aim was for the EU to recycle at least 85% of electrical and electronics waste equipment by 2016 (European Commission, 2020c). The directive is based on the principle of extended producer responsibility to create the link between the production phase and the waste phase of a product (Sander et al., 2008). Producer responsibility is a concept “that manufacturers and importers of products bear a degree of responsibility for the environmental impacts of their products throughout the products’ life-cycles […]” (Davis, 1994). Actors involved in the life cycle of EEE are producers, distributors, consumers and operators of treatment plants (Sander et al., 2008).

Each European Union member state has adopted its own enforcement and implementation policies using these directives as guides. Some member states, such as Austria, divided the Directive into its component parts, and implemented it in stages, using a number of different ordinances (JRC, 2007), e.g., the Elektroaltgeräteverordnung EAG-VO is implemented by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water (RIS, 2020).

Batteries are not included in RoHS and WEEE, there is a separate EU Battery Directive (2006/66/EC), which regulates the manufacturing and disposal of batteries (European Commission, 2020b). Batteries are not investigated in this study, see **chapter 2**.

1.3. Research focus of this PhD thesis

There exists no complete list of metals and their contents in smartphones. Although compliance for RoHS is tested in different setups, not every single product can always be tested (Nokia personal communication, 2013). In addition, many non-compliant products are being sold in the EU due to a weaknesses in regulatory enforcement (EU Commission, 2017). Smartphones have been termed as important metal carrier in several studies (e.g., Gradel et al., 2011; Reuter et al., 2013). Yet, apart from one current study (Holgersson et al., 2018), no detailed numbers are available for the exact metal content in smartphones post 2012; only numbers for older mobile phones pre 2012 exist (see for example Sarath et al., 2015). This also implies that data of metals currently in stock and potentially available in the future for recycling are lacking, and inquiries to determine future special metals demand in regards to WEEE thus remain unanswered.

Additionally, several misconceptions exist regarding the recycling of certain metallic elements from smartphones. Continuously, well-meant collections stating to recycle, for example, Rare Earth Elements or tantalum from smartphones (e.g., Nabu, 2020) can be found. Thus, lack of data and even faulty data on metallic elements for the recycling of smartphones prevail.

Although many efforts and initiatives for collection and recycling of smartphones exist, recycling rates have not significantly increased, and concepts for sensitizing consumers for these issues are still in need (e.g., Huisman et al., 2017). Information and education about resources and recycling topics have been identified as one way to address these issues (Reuter et al., 2013). Due to their ubiquitous use, almost everyone can relate to issues regarding smartphones. Thus, choosing smartphones as exemplary devices provides a good starting theme for an outreach study.

All these concerns accumulate in the three main research question of this thesis, with a clear raw materials focus on smartphones:

1. **Which metallic elements can be found in smartphones and which quantities?**
2. **Which of these are the most important metallic elements in smartphones with respect to economic importance, potential supply risks, sustainability, and recycling?**
3. **How can consumers be sensitized for improved resource appreciation and smartphone recycling?**

In this thesis, analytical and theoretical methods are combined to answer the three research questions. The analytical method for research question 1 will be addressed in **chapter 2** and summarized with the publication in **chapter 3**. The analytical and theoretical methods for research question 2 will be addressed in **chapter 4** and are summarized with the publication in **chapter 5**. In **chapters 6, 7,** and **8, research** question 3 will be addressed.

1.4. References

Bloomberg News. https://www.bloomberg.com/news/articles/2012-06-29/before-iphone-and-android-came-simon-the-first-smartphone accessed Aug 2020

Davis G (1998). Is There a Broad Principle of EPR? In K. Jönsson & T. Lindhqvist (eds.), Extended Producer Responsibility as a Policy Instrument – what is the Knowledge in the Scientific Community? AFR-Report 212. Stockholm: Swedish Environmental Protection Agency.

Enough Project (2009). From Mine to Mobile Phone: The Conflict Minerals Supply Chain. Report. https://enoughproject.org/reports/mine-mobile-phone accessed Aug 2020

EU Commission (2017). Press statement https://ec.europa.eu/commission/presscorner/detail/en/MEMO_17_5302 accessed July 2020

EU (European) Commission (2020a). A new Circular Economy Action Plan For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, The European Economic and social committee and the committee of the regions. https://ec.europa.eu/info/sites/info/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf accessed Aug 2020

EU Commission (2020b). Battery- Directive https://ec.europa.eu/environment/waste/batteries/ accessed Aug 2020

EU Commission (2020c). WEEE- Directive https://ec.europa.eu/environment/waste/weee/index_en.htm accessed Aug 2020

EU Commission (2019a). REACH- Directive https://ec.europa.eu/environment/chemicals/reach/reach_en.htm accessed Aug 2020

EU Commission (2019b). RoHS- Directive https://ec.europa.eu/environment/waste/rohs_eee/index_en.htm accessed Aug 2020

EU Parliament (2017). Conflict minerals: The truth behind your smartphone. Video and transcript. Multimedia Center. Download at https://multimedia.europarl.europa.eu/en/conflict-minerals-the-truth-behind-your-smartphone_D001-ESN-000317INT_ev accessed July 2020

Feinstein, N.W. and Kirchgasler, K.L. (2015). Sustainability in Science Education? How the Next Generation Science Standards Approach Sustainability, and Why It Matters. Science Education, 99(1): 121-144. https://www.doi.org/10.1002/sce.21137

Gartner Information Technology Glossary. https://www.gartner.com/en/information-technology accessed Aug 2020

Gartner (2019). https://www.techradar.com/news/smartphone-market-set-for-biggest-ever-decline accessed Aug 2020

Graedel TE, Allwood J, Birat JP, Reck BK, Sibley SF, Sonnemann G, Buchert M, Hagelüken C (2011). Recycling Rates of Metals – A Status Report.. ISBN 978-92-807-3161-3. https://www.resourcepanel.org/reports/metal-recycling accessed Aug 2020

Holgersson BS, Teenari M, Bjoerkman C and Cullbrand K (2018). Analysis of the metal content of small-size waste electric and electronic equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resources Conservation Recycling 133. https://doi.org/10.1016/j.resconrec.2017.02.011

Huisman J, Leroy P, Tertre F, Söderman M, Chancerel P, Cassard D, Løvik A, Wäger P, Kushnir D, Rotter VS, Mählitz P, Herreras L, Emmerich J, Hallberg A, Habib H, Wagner M, Downes S (2017). Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report. http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf accessed Aug 2020

IDC (International Data Corporation) (2020). Worldwide Smartphone Market Suffers Its Largest Year-Over-Year Decline in Q1 2020 Due to COVID-19 https://www.idc.com/getdoc.jsp?containerId=prUS46264320 accessed Aug 2020

Izatt RM (2016). Metal Sustainability: Global Challenges, Consequences, and Prospects. Wiley and Sons. 552 pages. ISBN: 978-1-119-00910-8

JRC Joint Reseach Center EU (2007). Implementation of the Waste Electric and Electronic Equipment Directive in the EU. Report to the European Commission. https://susproc.jrc.ec.europa.eu/activities/waste/Implementationweee.htm accessed Aug 2020

KnowYourMobile. Website for History of mobile phones. https://www.knowyourmobile.com/phones/the-history-of-mobile-phones-from-1973-to-2008-the-handsets-that-made-it-all-happen-d58/ accessed July 2020

Locke, S., Libarkin, J., & Chang, C.-Y. (2012). Geoscience Education and Global Development. Journal of Geoscience Education, 60(3), 199-200. www.https://www.doi/10.5408/1089-9995-60.3.199

Makov and Vivanco (2018). Does the Circular Economy Grow the Pie? The Case of Rebound Effects From Smartphone Reuse. Frontiers in Energy Research. https://doi.org/10.3389/fenrg.2018.00039

Nabu. Naturschutzbund. 10 Gründe ein Alt-Handy zu recyclen. https://www.nabu.de/imperia/md/content/nabude/konsumressourcenmuell/150820-nabu-umwelttipps-handys.pdf accessed Aug 2020

Nokia. Personal correspondence. M. Michaels, 2013.

OECD (2019). Global Material Resources Outlook to 2060 – Economic drivers and environmental consequences, OECD Publishing, Paris. https://doi.org/10.1787/9789264307452-en.

OECD (2020). Extended producer responsibility. https://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm accessed Aug 2020

Pew Research Center (2018). Smartphone ownership on the rise in emerging economies. https://www.pewresearch.org/global/2018/06/19/2-smartphone-ownership-on-the-rise-in-emerging-economies/ accessed Aug 2020

Poulsen F (2010). Blood in the Mobile.The dark side of our cell phones. Movie Documentary, 83 min. Spacesheep Movies. https://www.imdb.com/title/tt1763194/ accessed Aug 2020

Purvis B, Mao Y, Robinson D (2019). Three pillars of sustainability: in search of conceptual origins. Sustainability Science. 14: 681–695. https://doi.org/10.1007/s11625-018-0627-5

RIS (Rechtsinformationssystem des Bundes) Austria (2020). Gesamte Rechtsvorschrift für Elektroaltgeräteverordnung, Fassung vom 09.07.2020 https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20004052 accessed Aug 2020

Sander K, Schilling S, Tojo N, van Rossem C, Verson J, George C (2008). The Producer Responsibility Principle of the WEEE Directive. Final Report to the Commission. DG ENV. Study Contract N° 07010401/2006/449269/MAR/G4. Ökopol.

Sarath P, Bonda S, Mohanty S, and Navak S (2015). Mobile phone waste management and recycling: Views and trends. Waste Management. 46. pp. 536-545 https://doi.org/10.1016/j.wasman.2015.09.013

Siewiorek S (2012). Generation smartphone. IEEE Spectrum. 49(9): 54-58. doi: https://dor.org/10.1109/MSPEC.2012.6281134

Statista (2019). Dossier Smartphones. Statista Study ID 12856, sources after IDC (Global Mobile Phone tracker) and Gartner. https://de.statista.com/statistik/studie/id/3179/dokument/smartphones-statista-dossier/ accessed July 2020

Statista (2020). Smartphones sales https://www.statista.com/statistics/263437/global-smartphone-sales-to-end-users-since-2007/ accessed July 2020

Unicef (2011). Photo of the Year 2011. https://www.unicef.de/informieren/aktuelles/photo-of-the-year/contest-2011 accessed Aug 2020

UN United Nations (2015). Sustainable Development goals. https://sdgs.un.org/goals accessed Aug 2020

Weigensamer & Krönes (2018). Welcome to Sodom. Documentary, 92 min. Blackbox Film & Medienproduktion GmbH. http://www.welcome-to-sodom.com

2. Materials and methods

In this chapter, the analytical methods for measuring the metallic content in smartphones are explained in detail. This investigation provides the data foundation for the PhD thesis and allows to address the first research question, with the published summary of the analytical method development given in **chapter 3**. The achieved data set is then further specified with a geoscientific and sustainable context **in chapters 4** and summarized in **chapter 5**.

The research methods applied for the second and third research questions are described in **chapters 4** and **6**, respectively.

2.1. Introduction to smartphone analysis

No standardized method exists for the analytical assessment of metallic elements in smartphones for the determination of metallic elements in preferably all components in one single analytical approach. This also results from the circumstance that devices need to be manually taken apart prior to the measurements from all components in each device; with many different parts, this is time consuming and laborious. Sample preparation methods given in the literature mainly apply acid digestion methods and are similar to IEC 62321 (Oguchi et al., 2010: Sarath et al., 2015; Dervisevic et al., 2010). IEC 62321 is a standard testing method developed by the International Electrotechnical Commission (IEC) to determine the hazards in electronic products for RoHS compliance (IEC, 2020).

In this work, a single step microwave digestion protocol was developed based on IEC 62321 (IEC, 2020). For the analysis of multiple samples with multiple ranges in different elements to be measured, a combination of measurement methods was applied: ICP-MS (inductively coupled plasma mass spectrometry) and ICP-OES (inductively coupled plasma optical emission spectrometry) measurements were combined for analysing of up to 57 elements, optimized and validated using a certified reference material.

All images in this chapter were taken by Britta Bookhagen, unless stated otherwise.

2.2. Smartphone sample preparation

Three smartphones, the top sellers from 2012 with different operating systems, were chosen for this investigation (Gartner, 2014). They provide a choice representative for the newer smartphone generation starting 2012 where devices already had miniaturized printed circuit boards (see also **chapter 3.8**, ESI figure 1).

For reliable data of each type, three devices of each model were investigated ('triplicate'). Smartphone types were Samsung Galaxy 5, Nokia Lumia, and IPhone 4s (**Figure 2.1**). This method provides data for investigation of within-device and within-model variability.

Batteries were excluded from analysis due to safety reasons. Battery weights were recorded. Batteries at EOL are treated in special recycling facilities and thus research data on these components is already available (e.g., Zeng et al., 2014).

***Figure 2.1**: Investigated smartphones (from left to right: Samsung Galaxy, Nokia Lumia, IPhone 4s)*

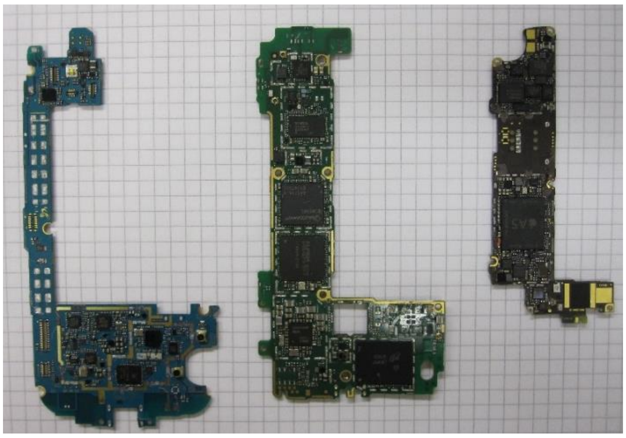

***Figure 2.2:** Their respective printed circuit boards (metal covers removed)*

All preparations and measurements were conducted at BOKU (University of Natural Resources and Life Sciences, Tulln) and the University of Vienna. For further details of study setup and measurements, see **chapter 3**.

Several preparation tests on different test smartphones were conducted to find the best possible way of preparing the solid samples for analysis. First, an overview of the components of smartphones and important metal parts of the different phone types needed to be determined. Detailed manual disassembly wearing gloves, separation, and weighing of each component was crucial as well as photographic documentation. The parts most important for the metal analysis were

- Printed circuit board (PCB) (**Figure 2.2**)
- Display-module
- Camera
- Loudspeaker
- Vibration motor

An approximate interpretation of smartphone content was possible after manual separation, see Apendix I. For the samples to be analysed with mass spectrometry, we preferred them to be present in a digested, liquid form to follow existing leaching procedures (see **chapter 2.3**). Also, a brief testing with laser ablation ICP-MS, disclosed too many small compartments and thus single measurements, especially for the PCB. Parts needed to be homogenized which lead to a liquid digestion. Thus, samples needed to be compartmentalized and samples should be as homogeneous as possible. For smartphone displays, a 1 cm x 1 cm piece cut through all layers was sampled using sharp metal scissors. Components were generally very heterogeneous, i.e., consisted of different metals, alloys, compounds, printed plastics with metals, and otherwise bonded materials (see **Figure 2.3**). Some metal covers were solded on the printed circuit board and had to be removed. A small sample size promised a relatively good separation of these compounds. Larger or heavy parts (e.g., the magnet of the smaller vibration motor) were fragmented until parts could be obtained. This meant a detailed manual preparation and a large number of samples in total was necessary.

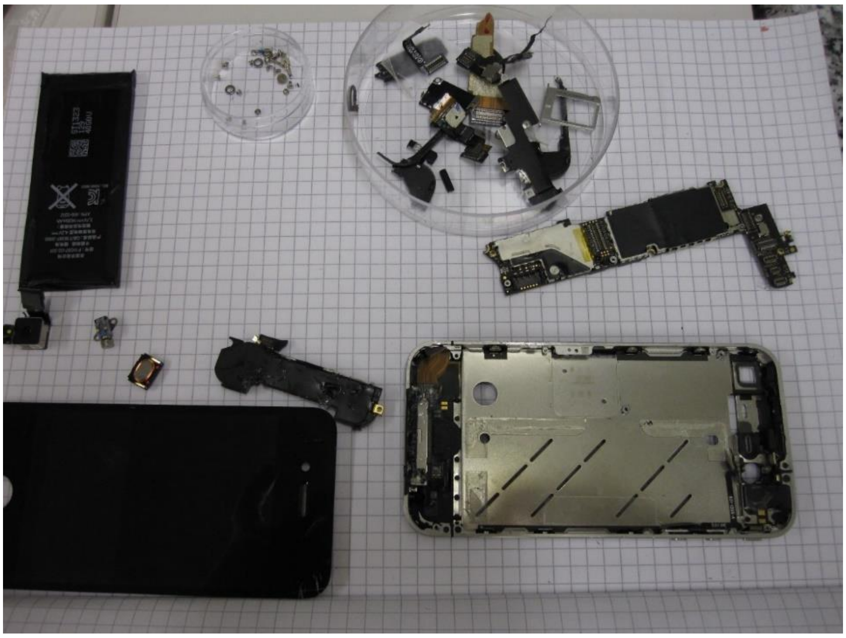

Figure 2.3: *Disassembled smartphone and its parts*

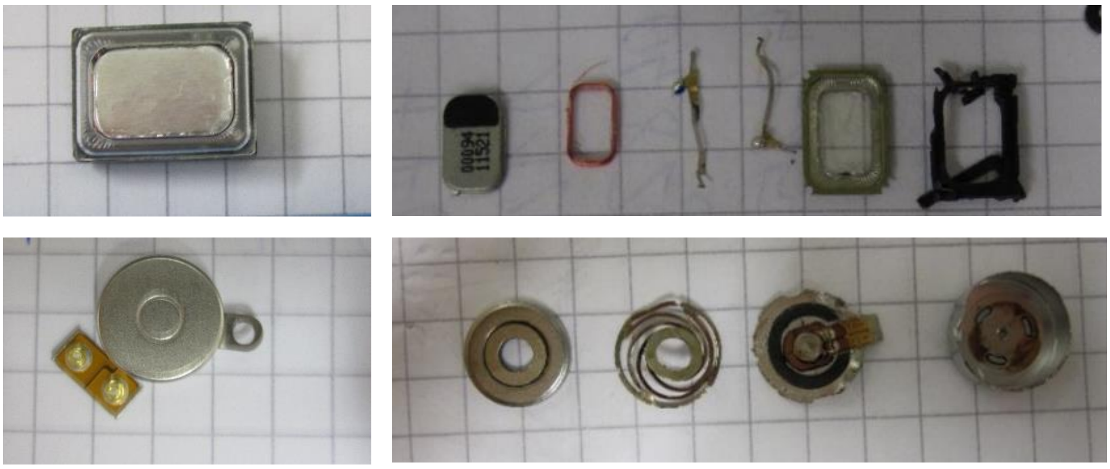

Figure 2.4: *Loudspeaker (top) and vibration motor (bottom) before and after compartmentalization. Weight loudspeaker: 1.67 g; weight vibration motor: 2.09 g*

For example, the loudspeaker consists of up to 6 different parts and several different materials, so does the vibration motor (**Figure 2.4**).

PCB were especially important, as they contain most of the important metals (Chancerel et al., 2013) but were especially heterogeneous with many miniature components (**Figure 2.2 and 2.7**). They can consist of up to 1000 different parts, most of them different capacitors. Metal covers are solded onto them which needed to be removed for separate investigation. Other single components (e.g., camera, vibration motor, and loudspeaker) were processed individually, even if mounted on the PCB in order to obtain component-specific metal content information from the analysis. Only for the PCB, a hammer mill was used to provide a fairly homogenous sample, and three samples of each PCB (i.e., nine samples from each phone) were investigated. During preparation, visual checks of milled samples were conducted via microscope to ensure fairly homogenous separation and determine milling time (see **Figure 2.6**). The final procedure consisted of milling for two minutes at 900 rpm in a Retsch RS 200 hammer mill (Retsch, Haan, Germany), using a hardened steel garniture (Figure 2.5) to obtain a powdered sample. Metal parts larger than 3 mm (e.g., thin metal covers, spring finger contacts or clips) were removed from the PCB beforehand, as they were too ductile to be milled. These parts were also processed and measured separately with the developed digestion protocol. Amounts of these parts were added to the results of the PCB in order to obtain data of the complete PCB. Although there were many tiny springs and clips, these were the parts expected to carry precious metals and thus needed to be thoroughly investigated.

***Figure 2.5**: Retsch Hammer mill set*

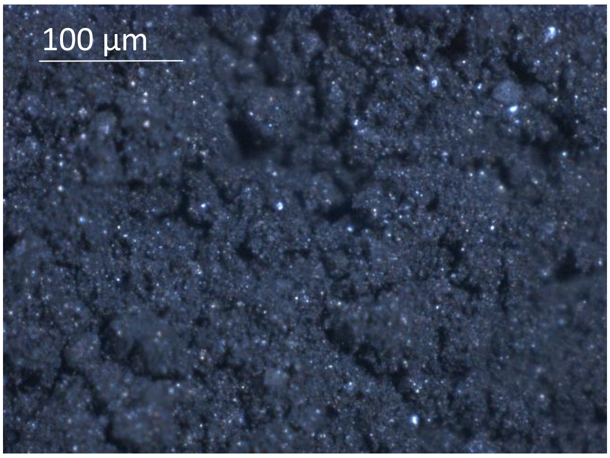

***Figure 2.6**: Light microscope photograph of milled PCB*

In order to estimate the content of plastic compounds, a separated loss on ignition (LOI) of grained PCB at 550°C (loss of C) in a 5h procedure was accomplished, using a Nabertherm N11/H (Lilienthal, Germany) furnace oven. Results corresponded with literature data and measured weights.

For another detailed and digital overview, Computer Tomographic (CT) pictures were taken at the Natural History Museum in Berlin (**Figure 2.7**). Numerous capacitors and parts are visible at the PCB. These pictures were also helpful to better disassemble electronic parts such as the vibration motor and loudspeaker (left in the picture).

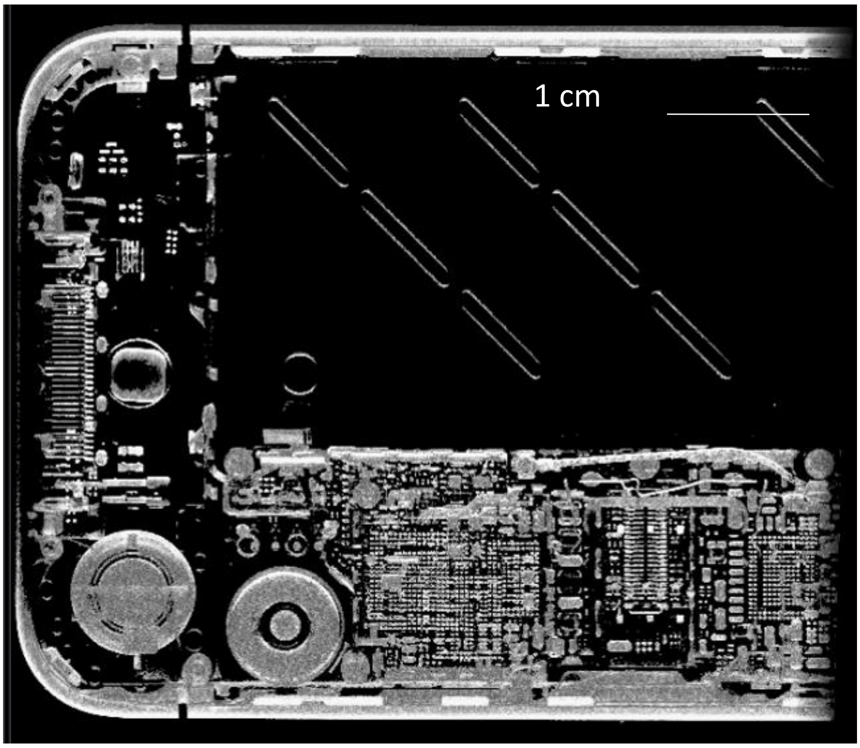

Figure 2.7: *Computer tomographic (CT) image from lower part of smartphone, depicting the variety of the many different parts.*

2.3. Microwave digestion procedure

After extensive considerations and testing with 34 samples of other smartphone devices, a sample size of 50 mg and a microwave digestion protocol were setup for triplicate smartphone sample preparation. For optimization of the digestion protocol, existing aqua regia leaching procedures (IEC 62321), literature protocols (Holgersson et al., 2018; Oguchi et al., 2011; Yamame et al., 2011) and direct manufacturer suggestions (Anton Paar, Graz, Austria), were adapted with the smartphone test samples. For these test considerations, other smartphone devices were used, as there were only three devices for each investigated smartphone for the final samples available. These samples were partly provided by the producers and partly by the author.

For the digestion, all metallic parts of the smartphone were weighed into the clean microwave vessels. First, 5 ml HNO_3 were added to the sample. Solutions were left for 10 minutes for possible reactions. Then 2 ml HCl were added. After another 3 minutes, 0.5 ml H_2O_2 was added to oxidize possible organic compounds. 1 ml HF was added directly before closing the vessels and starting the microwave program, using the following measures: max. pressure ramp 0,5 bar/s, IR max T = 170°C – max p = 60 bar, 800 Watt /10 min.

Before each digestion run, vessels were cleaned twice using a cleaning program (HNO_3 and HCl only) with the same program as the samples and then thoroughly rinsed with type I (18 MΩ cm) reagent grade water.

After cooling, 20 ml MQ (Type I reagent grade water, 18 MΩ cm) and 15 ml H_3BO_3 solution (γ = 27 mg m/l) were added and the solution was heated at 800 Watt for 5 min for complexation and dissolving of precipitated fluorides. Please see **chapter 3** for purities and concentrations of all used solutions.

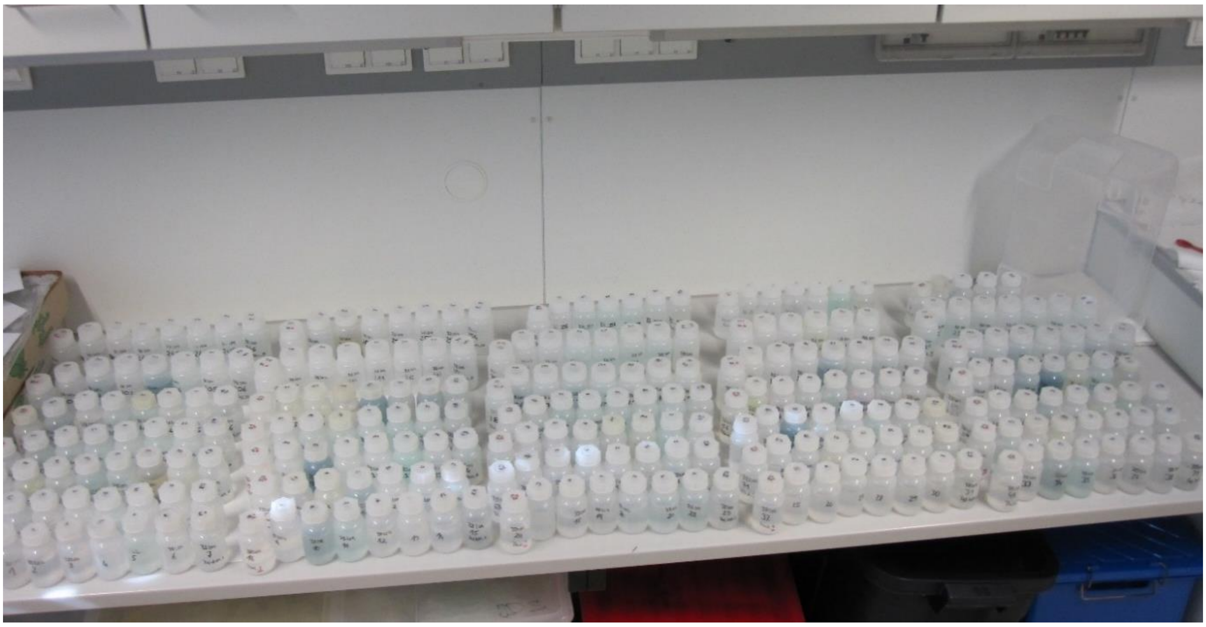

Figure 2.8: *Digested samples in plastic containers.*

After cooling, samples were poured into a PE-flask, diluted with type I reagent grade water to 100 mL and stored in pre-cleaned plastic containers in a dark cool room to prevent further reactions.

For the 3x3 analysed smartphones, over 280 samples in total were digested, see **Figure 2.8.**

All samples were digested in an Anton Paar Multiwave 3000. The microwave device allowed eight digestions samples for each run, of which six were smartphones samples, one was a **certified reference material** (CRM) and the last one a blank sample. CRM and blank were prepared following the same preparatory procedures with the same liquids as the samples.

The CRM is certified for electronic scrap (European Reference Material ERM®-EZ505) from BAM (Federal Institute for Materials Research and Testing, Berlin, Germany), certified for copper (Cu), nickel (Ni), silver (Ag), gold (Au), beryllium (Be), indium (In) and platinum (Pt). The material is a mixture of used printed circuit boards from various devices, additionally doped with Be, In and Pt, ashed and melted with pyrite (FeS_2). Described sampling resulted in 33 replicate digests of CRM, which were used for method optimization and validation. See **chapter 3** for detailed method validation and development.

2.4. Smartphone sample measurement

2.4.1. ICP-MS

A method was required to determine as many metals as possible in one single measurement step. Mass spectrometry (MS) is a technique that analyses ions based on their mass-to-charge (m/z) ratio to determine their identity and quantity in complex mixtures. It is capable of analysing almost all elements in the periodic table. The main components of a MS to achieve the essential functions are the ion source, the mass analyser, the detector, and the software for analysis (Nelms, 2005).

Atoms and molecules must first be ionized before they can be accelerated through the mass spectrometer and detected. The devices used for this analysis use an inductively coupled plasma (ICP) as ionization source, hence are termed **ICP-MS**.

For the samples to be ionized, they need to be digested first. Samples need to be present in an aqueous, acidified matrix. The solution is then vaporized using a nebulizer, and the mist is introduced into a high-temperature (6000 °C) argon plasma consisting of electrons and positively charged argon ions. In the plasma, the introduced material splits into individual atoms that lose electrons and become positively charged ions (anions are not detected by ICP-MS). The charged ions are then extracted through a series of cones into a quadrupole mass spectrometer where they are separated on the basis of their mass-to-charge ratio. When exiting the mass spectrometer, ions hit the electron multiplier, which serves as a detector. **Figure 2.9** presents a schematic display of an ICP-MS.

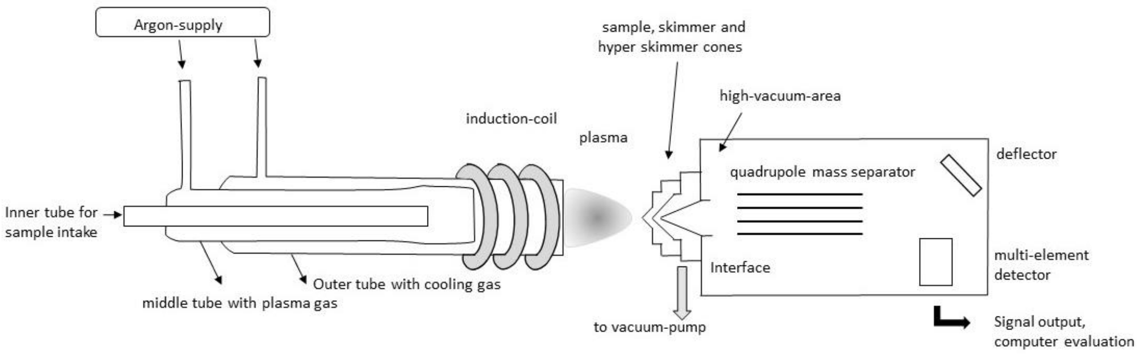

Figure 2.9: *Schematic display of main parts of quadrupole ICP-MS with detector; modified after Wiberneyt (2001). The plasma is generated using a torch with three concentric tubes: the inner tubes supplies the sample gas stream with the sample aerosol; the middle tube is needed for the plasma gas, and the third tube for the cooling gas to prevent the quartz from melting.*

Quantification was done using external linear calibration combined with internal normalization.

The software compares the intensities of the measured pulses to those from prepared standards, which are used to format the calibration curves, to determine the concentration of the element.

The cones for sample intake need to be cleaned or replaced after heavy use. **Figures 2.10 and 2.11** show cone replacements for NexIon 350D. All three cones are outside the vacuum area so they can be cleaned and replaced.

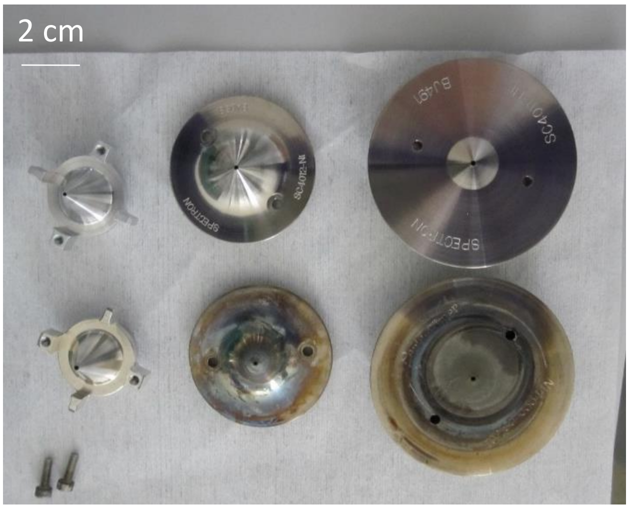

***Figure 2.10**: Hyperskimmer, skimmer and sampler cones for NeXion (top row: new replacements, bottom row: heavily used cones).*

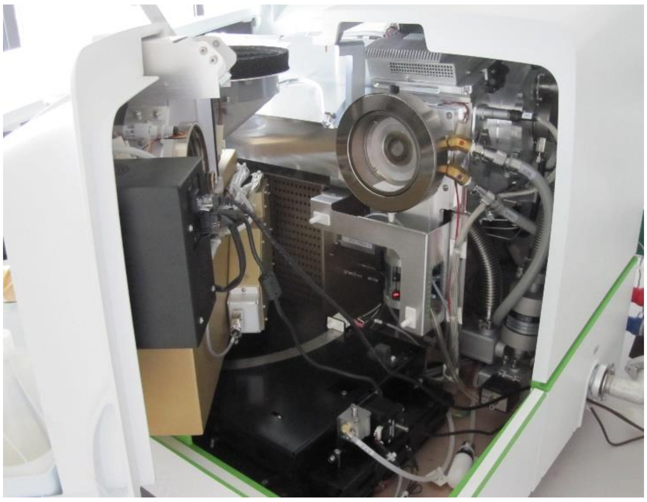

***Figure 2.11**: NexIon 350D, opened for maintenance. The cones fit at the round opening*

For the multi-elemental analysis of smartphone sample digests, two different ICP-MS were used: At the University of Vienna, Agilent 7700 (Agilent Technologies, Santa Clara, CA, USA) was used, at BOKU the NexION 350D (PerkinElmer) was employed.

The plasma, solvent and sample matrix can give rise to polyatomic interferences on many analytes, so modern quadrupole ICP-MS instruments use a collision/reaction cell (CRC) to reduce these interferences. For Nexion, the standard mode was used. For detailed devices setup, see **chapter 3.2**.

Detailed descriptions of ICP-MS and its application can be found in the literature, e.g., Nelms, 2005; Becker, 2007; Jakubowski et al., 2014.

2.4.2. ICP-OES

Another measuring method which uses the same ion-source is the inductively coupled plasma-optical emission (**ICP-OES**) system, which is based on optical emission spectroscopy. Thus, ICP-OES quantification is based on measurement of excited atoms and ions at the wavelength characteristics for the specific elements being measured. ICP-OES used for the analysis was Optima 5300 DV (Perkin Elmer, Waltham, MA, USA).

In general, due to the difference in element detection, the lower detection limit for ICP-MS can extend to 1 ng/kg (often referred to as parts per trillion (ppt)), whilst the lower limit for ICP-OES is usually 1 ng/g (often referred to as parts per billion (ppb).

2.4.3. Sample preparation for measurement: calibration, internal standards, quality controls

Sample digests were diluted with type I water or diluted HNO_3 to obtain concentration levels of the analytes within the working range of the methods.

The following **quality control solutions** were prepared:

For Perkin Elmer Optima 5300 DV and Agilent 7700 (University of Vienna), a multi-element solution (10 µg/l) was prepared from 1000 µg/l single element standards (all Merck-Millipore) and measured every 20 samples.

For Perkin Elmer Nexion, Multistandard M XIII and M IV (Merck-Millipore) were spiked with Au, Pd, Pt multi-element solution and the REE solution was prepared from single element standards (all Merck-Millipore).

In the ICP-MS, the use of **internal standards** serves both to correct changes in response over time (device drift) and to compensate for matrix-related non-spectral interference (signal suppression or increase). Customarily, samples and calibration solutions are mixed with the elements for internal standardization in equal concentrations. An internal standard element is assigned to each analyte and the calibration and measurement is then carried out in the analyzer / reference element intensity ratio based on the respective internal standard. Samples must be free from the selected element, for the multi-element smartphone samples, high masses were preferred. Selected internal standard was rhodium (10 µg/l) at University of Vienna and rhenium (1 µg /l) at BOKU. For the equation for determination of the calibration curve, the intensity of each sample analyte is divided by the intensity of each internal standard (see below).

Calibration

ICP-MS is an indirect measuring method that needs calibration to determine the relationship between signal and concentration. Several prepared calibration standards are measured to determine the slope of the calibration curve to obtain the linear line equation (i.e., for the calibration curve, the signal from the standard analysis is plotted against the standard concentration) using the following function:

$y = k*x + d$

y = signal, k = slope, x = sample concentration, d = Y-axis

Once the calibration function is known, the signal of the sample is measured and the concentration can be calculated using the linear straight line equation with a linear least-squares line to fit the data (for ICP-MS, the measured concentration is proportional, i.e. linear to the signal). The slope is a measure of analytical sensitivity.

External linear calibration was applied according to ISO standards using Perkin Elmer Optima 5300 DV and Agilent 7700 ICP-MS. Calibration was facilitated externally with single elements standards, using Merck Millipore.

A 'TotalQuant' method was applied for ICP-MS measurements on the PerkinElmer NexION 350D. The method is based on a one point calibration for elements in the calibration solution. All other elements are quantified with a response curve calculated via the NexION software. This procedure allows for the quantification of almost all elements measurable by ICP-MS. For Perkin Elmer Nexion, external standard with Multistandard M VI (Merck-Millipore) was used.

Data processing

Data from software of ICP-MS and ICP-OES was processed according to routine procedures for external linear calibration including blank correction and internal normalization (ISO, 2005). German DIN 32645 was used for calculation of Limit of Quantification (LOQ) and Limit of Detection (LOD) (DIN, 2008). Total combined uncertainties were calculated in accordance with ISO 5725 standards (ISO, 2001) and according to EURACHEM/GUM guidelines (Ellison & Williams, 2012). All procedures affecting uncertainties such as weighing, dilution, blank, and calibration were considered along with sample heterogeneity for calculating combined uncertainties.

2.4.4. Results

Results from measured samples are given in mg/kg or µg/g, i.e., the mass fraction of analysed metallic elements. This is useful for comparison between different studies (e.g., PCB from mobile phones and smartphones, where total weight is not important or not known, but the fractional content is). For example, the measured mass fraction of copper is 390,600 mg/kg in a smartphone. Mass fraction of analysed metallic elements is also used for comparison between smartphones and ores; ore grades are usually given in g/t, which is equivalent to mg/kg (see **chapter 5** in more detail).

Measured samples are also given in absolute amounts (total metallic content) in gram. This is useful for interpolation of total amounts of metallic elements for a larger number of devices, e.g., the content of copper in one smartphone is 6.50 g.

See **appendix II** (a and b) for complete smartphone measurement results. Uncertainties (u_c) correspond to total combined uncertainties ($k = 1$) from each triplicate samples for each element for separate smartphones. Detailed results are described for PCB in **chapter 3**.

2.5. References

Basel Convention (2012). Where are WEEE in Africa? Finding from the Basel Conventiion E-Waste Africa Programme. Available at http://www.basel.int/Portals/4/Basel%20Convention/docs/pub/WhereAreWeeInAfrica_ExecSummary_en.pdf accessed July 2020

Becker JS (2007). Inorganic Mass Spectrometry: Principles and Applications. John Wiley & Sons Ltd; 71 pages.

Buchanan PC, Koeberl C, Reimold WU (1999). Petrogenesis of the Dullstroom Formation,Bushveld Magmatic Province, South Africa. Contributions to Mineralogy and Petrology. 137: 133-146.

Chancerel P, Rotter VS, Ueberschaar M, Marwede M, Nissen NF, Lang K (2013). Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment. Waste Management and Research. 31. pp. 3-16 https://doi.org/10.1177/0734242X13499814

Dervisevic I, Minic D, Kamberovic Z, Cosovic Z, Ristic M (2013). Characterization of PCBs from computers and mobile phones, and the proposal of newly developed materials for substitution of gold, lead and arsenic. Environmetal Science and Pollution Research, **20,** 4278-4292. https://doi.org/10.1007/s11356-012-1448-1

Graedel TE, Allwood J, Birat JP, Reck BK, Sibley SF, Sonnemann G, Buchert M, Hagelüken C (2011). Recycling Rates of Metals – A Status Report. ISBN 978-92-807-3161-3. https://www.resourcepanel.org/reports/metal-recycling accessed July, 2020

Holgersson S, Teenari BS, Bjoerkman M, Cullbrand K (2018). Analysis of the metal content of small-size Waste Electric and Electronic Equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resources Conservation Recycling. 133:300–308.

IEC (International Electrotechnical Commission) https://webstore.iec.ch/publication/6834 accessed July 2020

Jakubowski N, Horsky M, Roos PH, Vanhaecke P and Prohaska T (2014). Inductively Coupled Plasma Mass Spectrometry. In: Prohaska T, Irrgeher J, Zitek A, Jakubowski N (Eds): Sector Field Mass Spectrometry for elemental isotopic analysis. The Royal Society of Chemistry. Cambridge. https://doi.org/10.1039/9781849735407-00208

Nelms S (2005). Inductively coupled plasma mass spectrometry handbook. Oxford: Blackwell publishing LTD. 285 pages. www.doi.org/10.1002/9781444305463

Oguchi M, Murakami S, Sakanakura H, Kida A, Kameya T (2011). A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Management. 31:2150–2160. https://doi.org/10.1016/j.wasman.2011.05.009

Perkin Elmer (2016). NeXion Brochure https://www.perkinelmer.com/pdfs/downloads/BRO_NexION350ICPMSBrochure.pdf

Sarath P, Bonda S, Mohanty S, and Navak S (2015). Mobile phone waste management and recycling: Views and trends. Waste Management 46. https://doi.org/10.1016/j.wasman.2015.09.013

Schönbächler M. (2016). Inductively Coupled Plasma Mass Spectrometry (ICP-MS). In: White W. (eds) Encyclopedia of Geochemistry. Encyclopedia of Earth Sciences Series. Springer. https://doi.org/10.1007/978-3-319-39193-9

Shannor M, Veksler IV, Hecht L, Harris C, Romer ML, Manyeruke T (2018). Small-scale Sr and O isotope variations through the UG2 in the eastern Bushveld Complex: The role of crustal fluids. Chemical Geology. 485; 100-112 https://doi.org/10.1016/j.chemgeo.2018.03.040

Tredoux M, Oberthuer T, Reid D and Trumbull R (2009). Platinum Value Chain. 11th Conference Proceedings, 11th SAGA Biennial Technical Meeting and Exhibition, cp-241-00123. https://doi.org/10.3997/2214-4609-pdb.241.tredoux_abstract

Wiberneyt N (2001). Einsatz der ICP-Massenspektrometrie zur Multielementbestimmung in biologischen Proben. Dissertation Thesis. 214 p. Hamburg.

Yakubchuk A, Nikishin AM (2004). Noril'sk- Talnakh Cu-Ni-PGE deposits: A revised tectonic model. Mineralium Deposita 39(2):125-142.

Yamane LH, de Moraes VT, Espinosa DCR, Tenorio JAS (2011). Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. Waste Management 31(12):2553–2558. 10.1016/j.wasman.2011.07.006

Young SB, Fonseca A, Dias G (2010). Principles for responsible metals supply to electronics. Social Responsibility Journal. Vol. 6, No. 1, 126-142.

Zeng X, Li J and Singh N (2014). Recycling of Spent Lithium-Ion Battery: A Critical Review. Critical Reviews in Environmental Science Technology, 44, 10. https://doi.org/10.1080/10643389.2013.763578

3. Development of a versatile analytical protocol for the comprehensive determination of the elemental composition of smartphone compartments on the example of printed circuit boards

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Article published by Journal **Analytical Methods, 2018,**10**, 3864-3871**
https://doi.org/10.1039/C8AY01192C

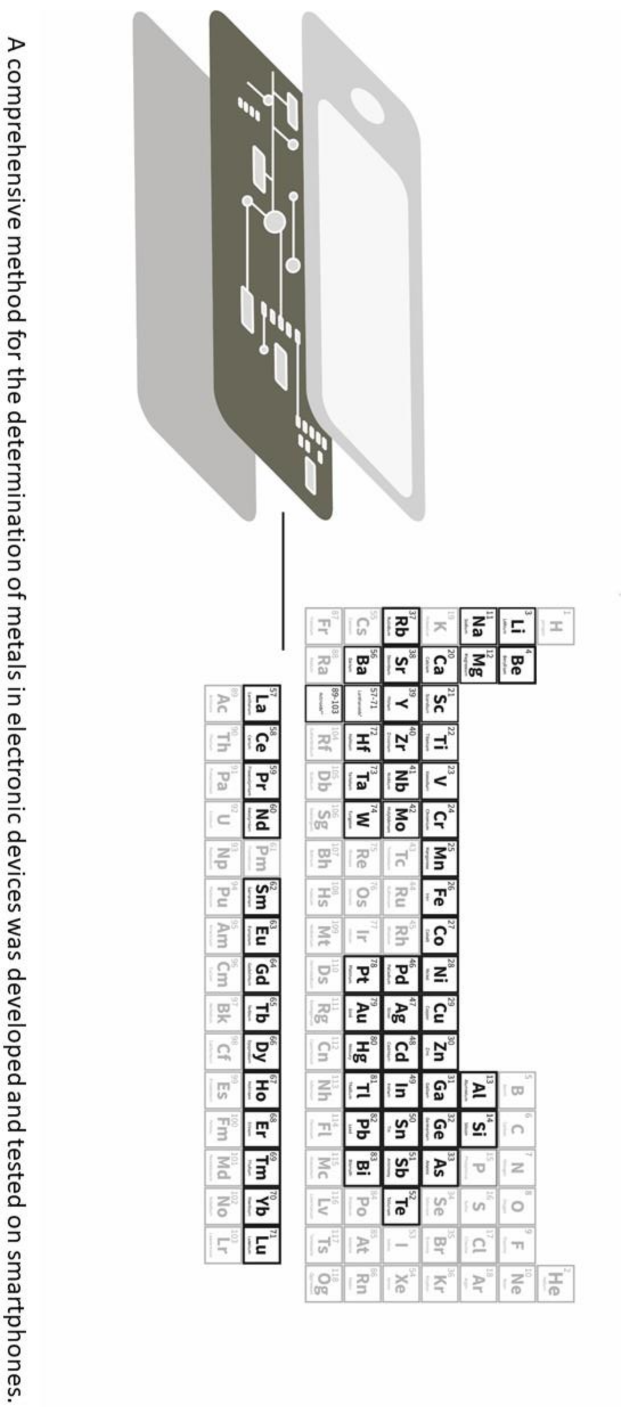
Submitted 10 April 2018, accepted 23 July 2018

Abstract

A versatile approach to determining the elemental content of more than 50 elements in different components of electronic devices on the example of smartphones was developed. The analytical protocol is based on accurate disassembly of smartphones, a single processing microwave-assisted acid digestion followed by ICP-OES and ICP-MS measurements. Method optimization and validation were performed using the certified reference material ERM®-EZ505 electronic scrap. Combined uncertainties revealed measurement uncertainty and sample heterogeneity as main contributors. The contents of up to 57 elements could be quantified in the certified reference material ERM®-EZ505 electronic scrap. The results of the certified elements Au, Be, Cu, In, Ni, Pd, and Pt overlapped within their uncertainties with the certified range and revealed recoveries of 100 % ± 16 %. Only Ag shows incomplete recoveries (75 % ± 35 %). The validated method was applied to all metal-containing components of selected smartphones, excluding batteries. The contents of up to 57 elements could be quantified and are presented exemplarily for printed circuit boards, which represent the most complex components in the investigated smartphones and thus limit the capability of the method. The ten most abundant elements in decreasing order are Cu, Fe, Si, Ni, Sn, Zn, Ba, Al, Cr, Ti, which comprise approx. 80% of the weight of the printed circuit boards. The method allows for the determination of metal content in various

parts of modern smartphones, providing the basis for the estimation and prediction of future metal usage and thus the comprehensive investigation of recycling and circular economy aspects.

Graphical abstract



3.1. Introduction

A comprehensive knowledge of the elemental composition of electronic products is essential for the assessment of potential metal demand as well as future recycling possibilities. Recycling of electronic products is still a substantial challenge even though it has outstanding economic and environmental benefits as well as positive resource conservation aspects. 1-3 In electronics, a large number of chemical elements are processed in chemical compounds, alloys and smallest components.2,3 Due to the content of hazardous metals, electronic waste may also pose a risk to the environment and health if products are not treated accordingly at their end of life stage.[2-4]. Consumer electronics such as ICT (information and communication technology) devices have lately been termed as a significant application of metals with unique properties, such as In, Ga, Ge, and Rare Earth Elements.3,5,6 The number of sold mobile phones has increased constantly, with a total of 1.8 billion devices sold worldwide in 2016, of which 1.4 billion were smartphones and 0.4 billion common mobile phones.[7,8] Smartphones are defined as more complex mobile phones with an operating system for apps and internet feasibility as well as (in most cases) a touch screen and other features as integral parts.[9]

Several studies on common mobile phones of older models released to the market before 2012 have been carried out and summarized data for the metal content, toxicological considerations and recycling options are available.12 To our knowledge, the only recently published data on smartphone devices investigated 36 metals in a two-step processing method, focusing on the printed circuit boards (PCB) of bulk smartphones from manufacturing years 2006-2013.13 PCB contain the largest number of different elements and have an extremely heterogeneous composition in terms of materials, generally containing plastics/polymers, ceramics, base metals, precious metals as well as toxic heavy metals.[3,10,13,14-16,18] So far, only little is known about the exact composition considering all metals in specific smartphone models and the composition of different sub-components other than PCB, such as loudspeakers or vibration motors.

Comparability of the limited existing data for smartphones is also challenging: Due to different design and techniques from different producers, some devices have important electronic components such as the vibration motor, the magnets (earphones and loudspeaker) and the camera mounted on the PCB, whereas these parts are located elsewhere within the phone in other devices. Thus, comprehensive data of the elemental content for entire smartphone devices with all subcomponents is imperative to address all essential aspects regarding e.g. environmental impact, toxicity, raw material consumption or recycling.

No standard method exists for the analytical assessment of metals in smartphones focusing on the determination of a comprehensive maximum number of metals in preferably all components of a smartphone in one single analytical approach. This results also from the circumstance that the manual separation of all components in each device is not straightforward. Sample preparation methods given in literature mainly apply acid digestion methods[9,12,14, 10, 18] similar to IEC 62321.[19] IEC 62321 is a standard test method developed by the International Electrotechnical Commission (IEC) to determine the hazards in electronic products. In Europe, these substances are regulated by the RoHS directive (Restriction of Hazardous Substances). IEC 62321 describes the testing methods for compliance of these restricted materials (lead, mercury, cadmium, hexavalent chromium, and two types of polybrominated flame retardants).

Research in this area can largely be categorized based on the type of materials of interest, i.e., polymers or metals. Recycling companies generally optimize analytical methods in-house to meet individual needs and requirements. These methods are often based on pyrolysis which is suitable for large batches,16 and focus on a limited number of selected metals of economic interest such as Ag, Au, Pd and Pt.3 Other methods concentrate either on the toxicity,[10] specific elements of interest, such as gold5 or copper,[11] or on specific components such as the display,[18,21] or on the PCB only.[11, 13,15] Analytical techniques that have been applied for the determination of the elemental composition of digested electronic scrap include inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectrometry (ICP-OES), Flame Atomic Absorption Spectrometry (AAS), and electrogravimetry.[9,10,12,14] According to IEC 62321, digestion of samples before ICP-MS/ICP-OES is usually completed using aqua regia leaching. Solid analysis has been accomplished by X-ray fluorescence (XRF) or scanning electron microscopy (SEM) and Atomic Fluorescence Spectroscopy (CV-AFS).[18,19]

To the best of our knowledge, there is no analytical protocol available to assess the maximum number of metals in different components of smartphones in a single processing approach. Here, we provide an analytical approach based on microwave-assisted acid digestion with subsequent multi-elemental analysis by ICP-MS and ICP-OES, optimized and validated on ERM®-EZ505 (reference material for electronic scrap with pyrite),[22] and applied to representative models of smartphones.

3.2. Experimental

Sample preparation (manual disassembly, milling and weighing), microwave digestion and ICP-MS and ICP-OES measurements were performed at the Department of Environmental Geosciences, University of Vienna (UNIVIE). Complementary ICP-MS measurements were carried out at the VIRIS Laboratory of the Department of Chemistry, University of Natural Resources and Life Sciences, Vienna (BOKU).

Manual disassembly, wearing clean single-use nitrile laboratory gloves to prevent contamination, was performed in a separate weighing room. All other preparatory procedures were performed in clean rooms at both facilities.

3.2.1. Reagents

UNIVIE (University of Vienna)

- Type I reagent grade water (18 MΩ cm) (F+L GmbH, Vienna, Austria)
- HNO_3 Suprapur® 65 % w/w (Merck-Millipore, Darmstadt, Germany)
- HCl Suprapur®, 30 % w/w (Merck-Millipore)
- H_2O_2 Suprapur®, 30 % w/w (Merck-Millipore)
- H_3BO_3 EMSURE® ACS, ISO, (Merck-Milipore), for Borate complexation (400 mg H_3BO_3 / digestion)
- HF (p.a. 40 %) EMSURE (Merck-Millipore)

BOKU (University of Natural Resources and Life Sciences)

- Type I reagent-grade water (18 MΩ cm) (F+L GmbH, Vienna, Austria), further purified by sub-boiling distillation (AHF Analysentechnik, Tuebingen, Germany)
- HNO_3 (65 % w/w, Merck-Millipore), purified by double sub-boiling using a DST-1000 sub-boiling distillation system (AHF Analysentechnik)
- Polyethylene (PE) flasks, tubes and pipette tips (VWR International, Radnor, USA) were pre-cleaned using HNO_3 (10 % w/w and 1 % w/w respectively)

3.2.2. Certified reference material

A certified reference material (CRM) for electronic scrap (European Reference Material ERM®-EZ505)22 from BAM (Federal Institute for Materials Research and Testing, Berlin, Germany) certified for copper (Cu), nickel (Ni), silver (Ag), gold (Au), beryllium (Be), indium (In) and platinum (Pt) was used for method optimization and validation. The material is a mixture of used printed circuit boards (PCB), additionally doped with Be, In and Pt, ashed and melted with pyrite (FeS_2).

3.2.3. Samples

Smartphone test devices (34 samples from different brands) were used for the optimization of the following processing steps in order to develop a single versatile protocol independent on the type of device: (1) manual disassembly of all parts (2) hammer milling (PCB only) (3) microwave-assisted acid digestion (4) ICP-MS/ICP-OES measurements of the digested samples.

The analytical protocol was finally applied exemplarily to three models of smartphones released to the market in 2012 from the brands Apple Inc., Nokia and Samsung Electronics Co. with highest sale numbers in 2012.[23,24] Three devices of each model were investigated and further processed (referred to as 'triplicate' in the manuscript; all data shown are presented anonymously for the smartphones and indicated as I, II and III, not reflecting the previous order). Smartphones from 2012 belong to a newer generation of smartphones, which already show a clear miniaturization of printed circuit boards. ESI Figure 1 visualizes this technological step.

3.2.4. Sample preparation

Metal components of the smartphone weighing < 100 mg (Analytical Balance AT201 Mettler Toledo, Ohio) were processed as a whole (e.g., including magnets of the camera). Larger parts (e.g., a small piece of the magnet of the larger vibration motor) were fragmented until smaller parts could be obtained. For smartphone displays, a 1 cm x 1 cm piece cut through all layers was sampled using sharp metal scissors.

Prior to microwave-assisted acid digestion, PCB were milled for two minutes at 900 rpm in a Retsch RS 200 hammer mill (Retsch, Haan, Germany), using a hardened steel garniture to obtain a powdered sample. All single components (e.g., camera, vibration motor, and loudspeaker) were processed individually from the PCB, even if mounted on the PCB in order to obtain component-specific metal content information from the analysis. Metal parts larger than 3 mm (e.g., thin metal covers, spring finger contacts or clips) were removed from the PCB beforehand, as they were too ductile to be milled. These parts were also processed and measured separately. The amounts were added to the results of the PCB in order to obtain data or the complete PCB. Three samples of each milled PCB section from each device were digested resulting in nine PCB samples per smartphone type.

A separated loss on ignition (LOI) of grained PCB at 550°C (loss of C) in a 5h procedure was accomplished in order to estimate the content of plastic compounds, using a Nabertherm N11/H (Lilienthal, Germany) furnace oven.

Metal parts with adhered plastics, which could not be separated manually (e.g., strip conductors and conductor paths) were disregarded as these parts represented minor constituents to the total metal content of an entire smartphone. These parts are likely to be largely composed of copper, usually representing the main material for conductors.3 Due to safety reasons, batteries were not investigated further. Battery weights were measured. Batteries at end-of-life (EOL) are treated in special recycling facilities and thus research data on these components is already available.[25]

3.2.5. Microwave-assisted acid digestion

The microwave digestion method was optimized based on existing aqua regia leaching procedures used elsewhere. IEC 62321[19] , literature protocols[10, 13,15] as well as direct manufacturer suggestions (Anton Paar, Graz, Austria), were adapted by using test samples. Asides the optimization of the microwave program, the reagent composition (HNO_3, HF, H_2O_2) was further optimized to guarantee complete digestion. (e.g., silicon dioxide and organic compounds in test samples were not dissolved completely without HF or H_2O_2.) The sample intake was decreased significantly (from a starting amount of 5 g) to obtain complete digestion. Complete sample digestion as well as achieved recoveries from CRM digests were considered as key parameters during optimization. The final sample intake for microwave digestion was approx. 50 mg. All samples were digested in an Anton Paar Multiwave 3000 (Anton Paar) using the following program: max. pressure ramp 0,5 bar/s, IR max T = 170°C – max p = 60 bar, 800 Watt /10 min. Before each digestion run, vessels were cleaned twice using a cleaning program (HNO_3 and HCl only) with the same program as the samples and then thoroughly rinsed with type I reagent grade -water. All metal parts were weighed into the clean microwave vessels. First, 5 mL HNO_3 were added to the sample. Solutions were left for 10 minutes for possible reactions. Then 2 mL HCl were added. After another 3 minutes, 0.5 mL H_2O_2 was added to oxidize possible organic compounds. 1 mL HF (p.a. 40 %) was finally added directly before closing the vessels and starting the microwave program. After cooling, 20 mL MQ and 15 mL H_3BO_3 solution (γ = 27 mg mL^{-1}) were added and the solution was heated at 800 Watt for 5 min for complexation and dissolving of precipitated fluorides. After cooling, samples

	Perkin Elmer Optima 5300 DV (UNIVIE)	**Agilent 7700x (UNIVIE)**	**Perkin Elmer NexION 350D (BOKU)**
Configuration / Parameter			
Sample Introduction	Quartz baffled cyclonic spray chamber	Peltier cooled double-pass Scott type spray	Peltier cooled cyclonic spray chamber
Nebulizer	µFlow (ESI, Omaha, Nebraska, US)	Micromist (Glass expansion, Melbourne, AUS)	µFlow (ESI)
RF Power	1450 W	1500 W	1300 W
Ar carrier gas	0.6 L min^{-1}	0.8 L min^{-1}	0.92 L min^{-1}
Ar make-up gas		0.4 L min^{-1}	0.75 L min^{-1}
Cell gas		4.0 mL min^{-1}	-
Measurement mode		Collision cell mode (He)	Standard mode
Measurement details			
Calibration	external with single element standards (Merck-Millipore)	external with single element standards (Merck-Millipore)	external with Multistandard M VI (Merck-Millipore)
Internal standard	Rhodium (10 mg L^{-1})	Rhodium (10 µg L^{-1})	Rhenium (1 µg mL^{-1})
Quality control solutions	multielement solution (10 µg L^{-1}) prepared from 1000 µg mL^{-1} single element standards (all Merck-Millipore) and measured every 20 samples	multielement solution (10 µg L^{-1}) prepared from 1000 µg mL^{-1} single element standards (all Merck-Millipore) and measured every 20 samples	Multistandard M XIII and M IV (Merck-Millipore) spiked with Au, Pd, Pt multielement solution and REE solution prepared from single element standards (all Merck-Millipore)

***Table 3.1**: Instrumental settings of the ICP-OES and ICP-MS instruments used for quantification, including*

were poured into a PE-flask, diluted with type I reagent grade water to 100 mL and stored in pre-cleaned plastic containers in the dark.

One method blank and one ERM®-EZ505 (sample intake: ~50 mg) were processed along with six samples within one microwave run. Blank and ERM®-EZ505 were prepared following the same preparatory procedures as the samples. In total, 33 replicate digests of ERM®-EZ505 were processed.

3.2.6. ICP-OES and ICP-MS measurements

All ICP-MS and ICP-OES parameters, standards and calibration methods at both facilities are listed in ESI 1. Multi-elemental analysis of sample digests was either done by ICP-OES (Optima 5300 DV, Perkin Elmer, Waltham, MA, USA) or ICP-MS (either Agilent 7700, Agilent Technologies, Santa Clara, CA, USA) or NexION 350D, PerkinElmer). Sample digests were diluted with water or diluted HNO3 to obtain 1 – 2 % (w/w) HNO_3 according to the working range of the methods. External linear calibration was applied according to ISO standards26 using Perkin Elmer Optima 5300 DV and Agilent 7700 ICP-MS. A 'TotalQuant' method was applied for ICP-MS measurements on the PerkinElmer NexION 350D. The method is based on a one point calibration for elements in the calibration solution. All other elements are quantified via a response curve calculated via the NexION software. This procedure allows for the quantification of almost all elements measurable by ICP-MS. Quality control samples and standards are also listed in **Table 3.1**. The corresponding method blank from

Table 3.2*: Certified and measured elemental contents of ERM®-EZ505: Certified values and uncertainties (I, II), analytical method (III) and limit of quantification (LOQ) (IV), measured values (n = 33) (V), as well as combined uncertainty (VI, VII) and recovery values (VIII). Combined uncertainty is given as mass fraction (VI) with a coverage factor of k = 1 and relative combined uncertainty (VII) is given with a coverage factor k = 2. Recoveries (VIII) are given in % from 33 replicate digests.*

	I	II	III	IV	V	VI	VII	VIII
Element	Certified mass fraction	U (k = 2) (certified value)	Method	*LOQ*	Measured mass fraction (n = 33)	u_c (k = 1)	$U_{c,rel}$ (k = 2)	Recovery ± *SD*
	/ mg g^{-1}	/ mg g^{-1}		/ µg g^{-1}	/ mg g^{-1}	/ mg g^{-1}	/ %	/ %
Cu	151	11	ICP-OES	0.5	167	5	6	110±3
Ni	4.70	0.08	ICP-OES	0.5	4.73	0.18	8	101±2
Ag	0.692	0.013	ICP-OES	0.1	0.52	0.16	61	75±23
	/ µg g^{-1}	/ µg g^{-1}		/ µg g^{-1}	/ µg g^{-1}	/ µg g^{-1}	/ %	/ %
Au	292	4	ICP-MS	0.1	265	15	11	91±5
Be	68.8	2.3	ICP-OES	0.0	69.6	3.1	9	101±3
In	91	7	ICP-MS	0.2	101	5	9	111±4
Pd	90.5	2.4	ICP-OES	0.1	91	11	24	100±11
Pt	8.5	0.8	ICP-MS	0.1	9.8	3.0	61	116±35

microwave digestion as well as analytical blanks (diluted HNO3 of the same HNO3 batch prepared for sample dilution) along with various quality controls were measured every 20 measurements.

3.2.7. Data processing

Data was processed according to routine procedures for external linear calibration,[26] including blank correction and internal normalization. German DIN 32645 was used for calculation of Limit of Quantification (LOQ) and Limit of Detection (LOD).[27] Total combined uncertainties (uc) were calculated in accordance with ISO 5725 standards[28] and according to EURACHEM/GUM guidelines.[29] Weighing, dilution, blank, calibration was considered along with sample heterogeneity for calculating combined uncertainties.

3.3. Results and discussion

3.3.1. Method optimization: Results for replicate analysis of ERM®-EZ505

Table 3.2 shows the results of the replicate analysis of ERM®-EZ505 and achieved recoveries of the eight certified elements, including combined uncertainty (u_c) and limits of quantification (LOQ). Combined uncertainties of measured values take into account contributions of single measurements (u_{meas}) as well as repeated digests (u_{rep}, as a measure of sample heterogeneity). Extended information about their respective contribution to the combined uncertainty can be found in ESI Table 1.

Recoveries for Be, Ni, and Pd are are close to 100 ± 1 %, Au and Cu within ± 10 % range, In within ± 11 % and Pt within ± 20 % range. Only Ag (± 25 %) shows incomplete recoveries.

ESI Table 1 also shows the results of 33 repetitive analyses of ERM®-EZ505 for all other, non-certified elements and their combined uncertainties, along with the relative contribution of the majour sources of uncertainty. In addition to the eight certified elements (Ag, Au, Be, Cu, In, Ni, Pd and Pt), 49 elements were measured, summing up to 57 elements in ERM®-EZ505: Al, As, Ba, Bi, Ca, Cd, Co, Cr, Fe, Ga, Ge, Hf, Hg, Li, Mg, Mn, Mo, Na, Nb, Pb, Rb, Sb, Si, Sn, Sr, Ta, Te, Ti, Tl, V, W, Zn, Zr, and 16 Rare Earth Elements (REE) Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Tm, Y, Yb. Fe is the most abundant element in ERM®-EZ505 (316 mg g-1 ± 10 mg g^{-1} (uc)). Hg and selected REE (Eu, Ho, Lu, Tb, Tm, Yb) have the lowest mass fraction of < 1 µg g-1. REE range from Nd with 106 µg g^{-1} ± 36 µg g^{-1} to Lu with 74 ng g^{-1} ± 14 ng g^{-1}.

3.3.2. Results for smartphone samples: Printed Circuit Boards (PCB)

Entire PCBs comprise triplicates from PCBs of each smartphone type plus separately measured metal covers and contacts which were mounted on PCBs. In this study, PCBs do not include camera, magnet/loudspeaker or vibration motor, if these parts were mounted on the PCBs. PCBs from different producers vary significantly in total weight, ranging from 12.27 g to 22.76 g. Therefore, both the element content as well as the total mass of elements are important parameter (see ESI Tables 2 and 3). The PCBs contains the most complex component mix. In total, 57 different elements could be quantified (see ESI Tables 4 and 5). Be and Tl are > LOQ in two PCB of the three smartphones and Hg and Te are > LOQ in the PCB of only one smartphone. In case of single REE, Gd and Pr were above LOQ in one of the three PCB (see ESI Table 4).

Figure 3.1 shows the average element contents and ranges. **Figure 3.2** shows the total amount per element of entire PCBs from the three smartphones (averaged triplicates from three PCBs of each model).

On average for the three investigated smartphones, the ten most abundant elements in decreasing order are Cu, Fe, Si, Ni, Sn, Zn, Ba, Al, Cr, Ca, which in sum comprise 78 % of the printed circuit board (corresponding to ca. 12.3 g in a PCB). Measured metals made up 74, 82 and 84 weight-% of each PCB respectively, see ESI Table 5. The remaining materials can likely be accounted to polymers, fibres and ceramic compounds.[15, 16].

3.3.3. Discussion

Benefits and limitations of the method

The microwave assisted digestion protocol proved to be successful for all smartphone components. Clear solutions with no residues could be observed. Measurements of the ERM®-EZ505 provide a comprehensive overview of 57 elements, which can be expected in electronic devices. Measurements of n=33 samples of ERM®-EZ505 show an adequate reproducibility considering the complexity and the limited applied sample amount (50 mg). Precision under reproducibility conditions for the certified elements ranged from 2 % (Ni), 3 % (Cu, Be), and 6 % (Au) to 11 % (Pd) and 30 % (Ag) (all values correspond to CV = coefficient of variation, which represents the ratio of the standard deviation to the mean of 33 repetitions). The determined quantities of all metals certified in ERM®-EZ505 overlapped within expanded uncertainties (Uc; k = 2) with the certified values for each run. Uncertainty values derive mostly from sample inhomogeneity. This proves that a substantial lower amount of ERM®-EZ505 is still utilizable and provides results within uncertainties for certified elements in the reference material, even though a larger uncertainty due to sample heterogeneity can be expected. Only Ag showed significantly lower recovery together with a large CV thus still overlapping within uncertainties. This might be explained by the use of HCl for the digestion resulting in a non-reproducible loss of Ag as AgCl.

Applying the method for smartphones, 50 elements of these 59 elements could be quantified (>LOQ) in the complex PCB of smartphones, providing substantially more information as compared to other studies. 13,9,14 Only one processing step is required as opposed to comparable studies, which e.g. used an additional pyrolizing step of the first leaching residue to measure 36 elements in total.13 In contrast to other methods, no prior sieving or magnetic-separation of samples was necessary.10,11,12. With approx. 50 mg and a precise manual disassembly of single smartphones, we used small sample amounts.

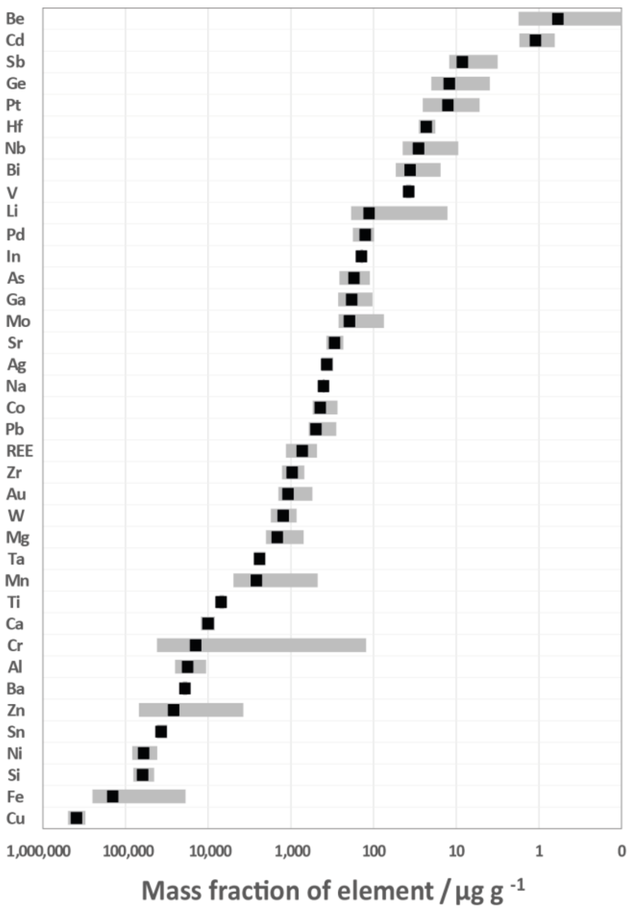


Figure 3.1: *Mass fraction of analysed metals in PCB in µg g^{-1}, sorted by increasing values. Black marker depicts average of PCB from three smartphones of different manufacturers for each element in µg g^{-1}. Grey lines indicate the range from lowest to highest determined values for metal mass fraction in µg g^{-1}. Rare Earth Elements (REE) are given as sum of all REE. Elements < 1 µg g^{-1}are not displayed.*

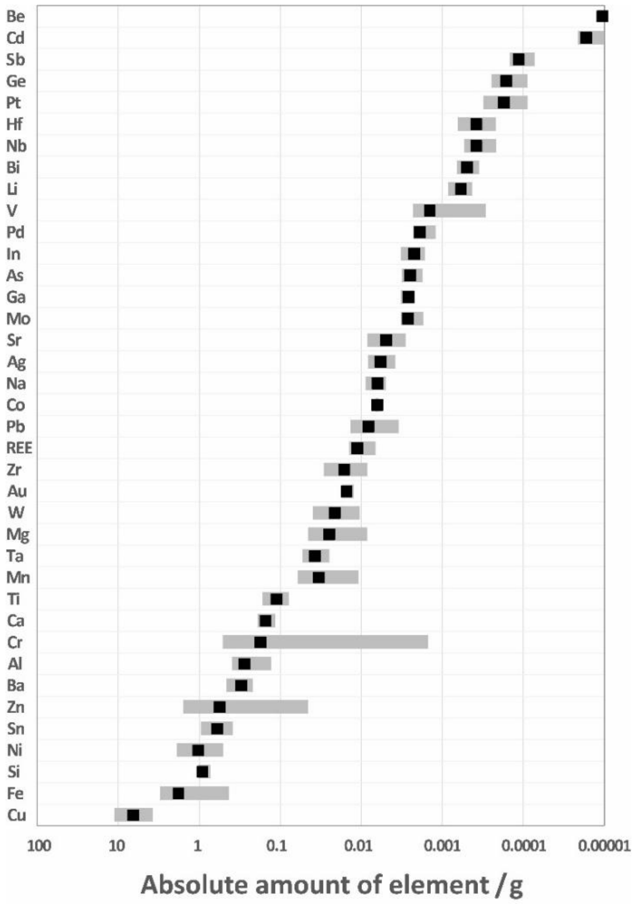


Figure 3.2: *Total averaged metal content for PCB in the three smartphones in gram, sorted by same order as Figure 1. Black marker depicts average content of PCB in the three smartphones. Grey lines show the range with minimum and maximum values of single smartphone contents. Rare Earth Elements (REE) are given as sum of all REE*

Elemental content in smartphone devices

ESI Table 3 provides comparative data of the total amount of elements in the PCB of the three smartphone types. High contrasting numbers, for example for Zn, can be accounted to the variability between smartphone brands. Smartphone model II had thin metal covers mounted on the PCB, mostly composed of Zn (1.57 g ± 0.10 g) and thus significantly increasing the Zn content of the PCB and contributing to a higher average for the three different smartphone models. Zn is only present at 0.046 g (± 0.002 g) and 0.069 g (± 0.012 g) in smartphones I and III, respectively. The composition of PCBs from smartphones given by Holgersson et al.[13] for Zn (who used average values from a batch of heterogeneous smartphones), corresponds to smartphone I and III. Methods applied to PCB analysis are only comparable to a certain extent as often no information is provided on the sample disassembly (e.g., dismounting of complex parts such as magnets/loudspeakers, vibrations motors from the PCB).

PCB weight of the total product weight is 13 %, 18 %, 11 % respectively for the three investigated smartphones. As depicted in ESI Figure 1, newer generation smartphones from 2012 have smaller PCB and also a larger (thus comparatively heavier) display, thus explaining the lower averaged weight percentage of PCB to comparable literature (21 % for mobile phones from 2001-201013, and 21 % for smartphones from 2004-201313 as well as 2-22 % for mobile phones from 2000-2007). Since the design has not changed significantly since then, we can assume to investigate a representative PCB from a recent device.

Due to declining sale numbers, common mobile phones (0.4 billion out of 1.8 billion sold total mobile phones) are of decreasing interest for future raw material demands.[10,12]

Detailed within-device and within-model variability can be shown from the assessed data within this study. ESI Table 6 displays both variabilities exemplary for smartphone I. The within-same device variability is below 10 % RSD proving the reproducibility of the applied analytical protocol. This within-device variability is adequately considering the fact that a PCB can contain between 600 to more than 1000 tiny capacitors (some of which weighing less than 0.01 mg). Thus, milling provided a representative mixture of the PCB. The within-model variability of e.g. smartphone model I (n = 3) is < 10 %. ESI Figure 2 visualizes the within-device and within-model variability**.** This differentiates our study from other studies, which usually investigate a bulk of different smartphones as a heterogeneous batch,13 as summarized in ref. 12. The large variability of the mass fraction of different metals in PCB between smartphone brands is shown in ESI Table 2.

Toxicity considerations

Our research only targeted metals and metal parts. Plastic components (polymers, etc.) and ceramics were not investigated. In this study, concentrations of Pb, Hg and Cd in all three PCBs are in agreement with RoHS directive restrictions (see Annex II: RoHS Pb < 0.1 %; Hg < 0.1 %; Cd > 0.01 %). Pb is 283, 598 and 607 µg g-1 respectively, Cd 1.7, 0.9 and 1.6 µg g-1 respectively, and Hg < LOQ, < LOQ, and 0.34 µg g-1 respectively. All other investigated metal components other than PCB were also within limits of toxicity restrictions of RoHS Annex II, as well.[30]

3.4. Conclusions

A comprehensive method for the investigation of the total elemental content was successfully optimized for the investigation of smartphone devices. The results allow for a more detailed look into single components smartphones and thus provide the basis for considerations of metal demand scenarios, which are currently assessed in a comprehensive study. We see a strong need for harmonized methods to determine the content in single components and the absolute amount of metals per electronic device for comparability between studies.

Because other information and communication technology devices such as tablets, notebooks and personal computers are of similar composition, this method can easily be adapted to analyse other ICT devices to reinforce metal demand scenarios for the coming years. As a result of extensive literature research, we further propose to provide data on the metal content of smartphones (and subcomponents of smartphones) and similar ICT devices not only in concentrations, but in total amounts of elements. Else, an estimation of recycled material would show substantial uncertainties.

3.5. Conflict of interest

There are no conflicts to declare.

3.6. Acknowledgements

We would like to thank Oliver Krüger, formerly BAM (Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany) and Melanie Diesner (VIRIS Laboratory BOKU) for technical support. We thank customer support from Anton Paar for support concerning the development of the microwave digestion protocol.

3.7. Authorship contribution

B. Bookhagen: Conceptualization, Methodology, Data curation, Investigation, Writing - original draft.

W. Obermayer: Data curation, Methodology.

C. Opper: Data curation, Methodology.

C. Koeberl: Supervision, Writing - review & editing.

T. Hofmann: Supervision, Writing - review & editing

T. Prohaska: Validation, Writing - review & editing, Supervision.

J. Irrgeher: Validation, Writing - review & editing, Supervision.

3.8. References

1. Environmental Protection Agency (EPA), https://www.epa.gov/smm/recycling-economic-information-rei-report , (accessed March 2018)
2. UNEP, Recycling Rates of Metals – A Status Report. A Report of the Working Group on the Global Metals Flows to the International Resource Panel. 2011.
3. C. Hagelüken and C. Corti, Gold Bull., 2010, **43** (3), 209.
4. European Commission (WEEE), http://ec.europa.eu/environment/waste/weee/index_en.htm , (accessed April 2018)
5. P. Chancerel, C.E.M. Meskers, C. Hagelüken, V.S. Rotter. *J. Indus. Ecol.* 2009. **13** (5), 791–810
6. A. Elshkaki, T.E. Graedel. J Clean Prod. 2013.**59.**260-273.
7. Statista, https://www.statista.com/statistics/263437/global-smartphone-sales-to-end-users-since-2007/ , accessed March 2018
8. Gartner Online Analysts https://www.gartner.com/newsroom/id/3816763 accessed April 2018
9. Oxford Online Definitions, https://en.oxforddictionaries.com/definition/smartphone , accessed April 2018
10. M. Oguchi, S. Murakami, H. Sakanakura, A. Kida, T. Kameya, Waste Manage., 2011, **31**, 9.
11. A.C. Kasper, G. B. T. Berselli, B. D. Freitas, J. A. S.Tenorio, A. M. Bernardes, H. M. Veit. Waste Manage., 2011, **31** (12), 2536.

12. P. Sarath, S. Bonda, S. Mohanty, S. Navak, Waste Manage., 2015. 46
13. S. Holgersson, B. S. Teenari, M. Bjoerkman, K. Cullbrand, Resour. Conserv. Recycl. 2017*,* **129**.
14. W. J. Hall & P. T. Williams, Resour. Conserv. Recycl., 2007, **51 (**3), 691-709.
15. L. H. Yamane, V. T. de Moraes, D. C. R. Espinosa, J.A.S. Tenorio, Waste Manage., 2011, **31**, 2553-2558.
16. C. Kasper, A.M Bernardes, H.M Veit. Waste Manage. Res.*,* 2011, **29** (7), 714.
17. M. C. Vats and S. K. Singh. Waste Manage.,2015, **45**, 280.
18. A. Dervisevic, D. Minic, Z. Kamberovic, V. Cosovic, M. Ristic. Environ. Sci. Pollut. Res., 2013,**20,** 4278-4292.
19. International Electrotechnical Commission (IEC), https://webstore.iec.ch/publication/6834 , accessed April 2018
20. European Commission, http://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm accessed March 2018
21. M. Ueberschaar, M. Schlummer, D. Jalalpoor, N. Kaup, V. S. Rotter, Recycling, 2017, 2 (1),7 doi:10.3390/recycling201000
22. BAM (Bundesagentur for Material Sciences). Certified Reference Material ERM®-EZ505. 2011. Berlin. Germany.
23. Statista web statistics https://de.statista.com/statistik/daten/studie/245936/umfrage/vergleich-der-absatzzahlen-von-samsungs-galaxy-s3-und-apples-iphone/ accessed April 2018
24. International Data Corporation (IDC) https://www.idc.com/promo/smartphone-market-share/vendor accessed April 2018
25. X. Zeng, J. Li, and N. Singh, Crit. Rev. Environ. Sci. Technol., 2014, **44**, 10.
26. ISO/IEC (International Organization for Standardization) 17025. General requirements for the competence of testing and calibration laboratories. 2005. Geneva, Switzerland.
27. DIN (German Institute for Standardization) 32645: Chemical analysis - Decision limit, detection limit and determination limit under repeatability conditions. 2008. Berlin, Germany.
28. ISO/IEC (International Organization for Standardization) 5725. Accuracy (trueness and precision) of measurement methods and results. 2001. Geneva, Switzerland.

29. S. L. R. Ellison and A. Williams (Eds). Eurachem/CITAC guide: Quantifying Uncertainty in Analytical Measurement, 3rd edition. 2012. ISBN 978-0-948926-30-3.

30. European Parliament, Annex II http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02011L0065-20160715&from=EN accessed April 2018

3.9. Electronic Supplementary Information (ESI)

ESI Table 1: *Measured values of certified (*) and non-certified elements of ERM®-EZ505: Analytical method used for investigation (TQ: Totalquant Method); LOQ and measurement result (average of n = 33); combined uncertainties (u_c, k = 1); relative contribution of measurement precision (u_{meas}) and replicate analysis (u_{rep}) to u_c.*

Element	Method	*LOQ* / µg g^{-1}	Mass fraction (measured data) (*n* = 33)	Combined uncertainty u_c	Relative contribution u_{meas} / %	Relative contribution u_{rep} / %
Al	ICP-OES	685	30.4 mg g^{-1}	1.6 mg g^{-1}	13	87
Ag*	ICP-OES	11	0.52 mg g^{-1}	0.16 mg g^{-1}	1	99
As	ICP-MS	0.63	266 µg g^{-1}	18 µg g^{-1}	56	44
Au*	ICP-MS	0.024	265 µg g^{-1}	15 µg g^{-1}	16	84
Ba	ICP-OES	9.7	2.40 mg g^{-1}	0.09 mg g^{-1}	76	24
Be*	ICP-OES	0.054	69.6 µg g^{-1}	3.1 µg g^{-1}	39	61
Bi	ICP-MS	0.010	85 µg g^{-1}	5 µg g^{-1}	13	87
Ca	ICP-OES	1936	18.9 mg g^{-1}	0.7 mg g^{-1}	5	95
Cd	ICP-MS	0.10	8.5 µg g^{-1}	1.4 µg g^{-1}	42	58
Co	ICP-MS	0.0094	255 µg g^{-1}	10 µg g^{-1}	30	70
Cr	ICP-OES	2.7	1.34 mg g^{-1}	0.10 mg g^{-1}	1	99
Cu*	ICP-OES	24	167 mg g^{-1}	5 mg g^{-1}	7	93
Fe	ICP-OES	55	316 mg g^{-1}	10 mg g^{-1}	11	89
Ga	ICP-MS	0.36	16.8 µg g^{-1}	2.9 µg g^{-1}	43	57
Ge	ICP-MS	0.26	3.7 µg g^{-1}	1.0 µg g^{-1}	65	35
Hf	ICP-MS	0.012	6.4 µg g^{-1}	3.2 µg g^{-1}	1	99
Hg	ICP-MS	0.078	0.4 µg g^{-1}	0.3 µg g^{-1}	80	20
In*	ICP-MS	0.010	101 µg g^{-1}	5 µg g^{-1}	35	65
Li	ICP-OES	0.54	13.0 µg g^{-1}	0.7 µg g^{-1}	<1	100
Mg	ICP-OES	49	1.66 mg g^{-1}	0.04 mg g^{-1}	19	81
Mn	ICP-OES	0.60	3.95 mg g^{-1}	0.20 mg g^{-1}	1	99
Mo	ICP-MS	0.054	242 µg g^{-1}	27 µg g^{-1}	4	96
Na	ICP-OES	318	11.4 mg g^{-1}	0.4 mg g^{-1}	60	40
Ni*	ICP-OES	16	4.73 mg g^{-1}	0.18 mg g^{-1}	70	30
Nb	ICP-MS	0.00049	35 µg g^{-1}	6 µg g^{-1}	65	35
Pb	ICP-MS	0.47	7.1 mg g^{-1}	0.3 mg g^{-1}	22	78
Pd*	ICP-OES	0.89	91 µg g^{-1}	11 µg g^{-1}	12	88

Table 1 continued

Element	ICP-Method	*LOQ* / ng g^{-1}	Mass fraction (measured data) (*n* = 33)	Combined uncertainty u_c	Relative contribution u_{meas} / %	Relative contribution u_{rep} / %
Pt*	ICP-OES	1.7	10.2 µg g^{-1}	3.5 µg g^{-1}	2	98
Rb	ICP-MS	0.030	5.7 µg g^{-1}	2.1 µg g^{-1}	17	83
Sb	ICP-MS	0.021	2.56 mg g^{-1}	0.13 mg g^{-1}	20	80
Si	ICP-OES	78	51.7 mg g^{-1}	1.7 mg g^{-1}	19	80
Sn	ICP-MS	0.13	9.9 mg g^{-1}	0.4 mg g^{-1}	25	76
Sr	ICP-OES	14	322 µg g^{-1}	10 µg g^{-1}	6	94
Ta	ICP-OES	4.1	0.79 mg g^{-1}	0.10 mg g^{-1}	2	98
Te	ICP-MS	0.0035	4 µg g^{-1}	6 µg g^{-1}	63	37
Ti	ICP-OES	20	2.05 mg g^{-1}	0.14 mg g^{-1}	31	69
Tl	ICP-MS	0.0024	11 µg g^{-1}	7 µg g^{-1}	<1	100
V	ICP-MS	0.017	31.5 µg g^{-1}	1.8 µg g^{-1}	58	42
W	ICP-OES	23	0.59 mg g^{-1}	0.10 mg g^{-1}	3	97
Zn	ICP-OES	22	17.9 mg g^{-1}	0.5 mg g^{-1}	17	83
Zr	ICP-MS	0.55	0.31 mg g^{-1}	0.08 mg g^{-1}	2	98
REE						
Ce	ICP-MS	83	36 µg g^{-1}	5 µg g^{-1}	44	56
Dy	ICP-MS	40	2.2 µg g^{-1}	1.2 µg g^{-1}	4	96
Er	ICP-MS	0.06	1.26 µg g^{-1}	0.15 µg g^{-1}	69	31
Eu	ICP-MS	0.06	0.48 µg g^{-1}	0.05 µg g^{-1}	80	20
Gd	ICP-MS	2.6	2.0 µg g^{-1}	0.7 µg g^{-1}	8	92
Ho	ICP-MS	0.02	0.58 µg g^{-1}	0.21 µg g^{-1}	7	93
La	ICP-MS	4.1	36 µg g^{-1}	5 µg g^{-1}	53	47
Lu	ICP-MS	0.04	74 ng g^{-1}	14 ng g^{-1}	28	72
Nd	ICP-MS	243	106 µg g^{-1}	36 µg g^{-1}	9	91
Pr	ICP-MS	71	7.1 µg g^{-1}	3.2 µg g^{-1}	5	95
Sc	ICP-MS	61	7.4 µg g^{-1}	3.1 µg g^{-1}	6	94
Sm	ICP-MS	0.55	11.4 µg g^{-1}	1.3 µg g^{-1}	7	23
Tb	ICP-MS	1.0	0.27 µg g^{-1}	0.07 µg g^{-1}	13	87
Tm	ICP-MS	0.02	74 ng g-1	10 ng g^{-1}	58	42
Y	ICP-MS	3.3	6.6 µg g-1	1.4 µg g^{-1}	21	80
Yb	ICP-MS	0.19	0.50 µg g^{-1}	0.06 µg g^{-1}	64	36

ESI Table 2: *Mass fractions of elements in printed circuit boards (PCB) from smartphones (n = 3) from three different manufacturers in µg g^{-1} from averaged triplicates of each phone. 'Min' corresponds to the lowest value from three smartphones. 'Max' corresponds to the highest value from three smartphones. Data is sorted by decreasing average mass fraction (see also Figure 3.1).*

Element	Mass fraction min	Mass fraction average (*n* = 3)	Mass fraction max
Cu	306 mg g^{-1}	391 mg g^{-1}	495 mg g^{-1}
Fe	19 mg g^{-1}	142 mg g^{-1}	251 mg g^{-1}
Si	45 mg g^{-1}	62 mg g^{-1}	80 mg g^{-1}
Ni	42 mg g^{-1}	60 mg g^{-1}	83 mg g^{-1}
Sn	31 mg g^{-1}	37 mg g^{-1}	42 mg g^{-1}
Zn	3.8 mg g^{-1}	26 mg g^{-1}	69 mg g^{-1}
Ba	18 mg g^{-1}	19 mg g^{-1}	20 mg g^{-1}
Al	11 mg g^{-1}	18 mg g^{-1}	25 mg g^{-1}
Cr	0.12 mg g^{-1}	14.16 mg g^{-1}	41.70 mg g^{-1}
Ca	8.3 mg g^{-1}	10.0 mg g^{-1}	12.3 mg g^{-1}
Ti	6.5 mg g^{-1}	7.0 mg g^{-1}	7.3 mg g^{-1}
Mn	478 µg g^{-1}	2608 µg g^{-1}	4940 µg g^{-1}
Ta	2023 µg g^{-1}	2385 µg g^{-1}	2804 µg g^{-1}
Mg	701 µg g^{-1}	1458 µg g^{-1}	2000 µg g^{-1}
W	855 µg g^{-1}	1236 µg g^{-1}	1744 µg g^{-1}
Au	551 µg g^{-1}	1081 µg g^{-1}	1410 µg g^{-1}
Zr	692 µg g^{-1}	960 µg g^{-1}	1280 µg g^{-1}
REE	485 µg g^{-1}	727 µg g^{-1}	1148 µg g^{-1}
Pb	283 µg g^{-1}	496 µg g^{-1}	607 µg g^{-1}
Co	274 µg g^{-1}	439 µg g^{-1}	543 µg g^{-1}
Na	391 µg g^{-1}	402 µg g^{-1}	412 µg g^{-1}
Ag	308 µg g^{-1}	367 µg g^{-1}	428 µg g^{-1}
Sr	232 µg g^{-1}	296 µg g^{-1}	372 µg g^{-1}
Mo	75 µg g^{-1}	195 µg g^{-1}	265 µg g^{-1}
Ga	103 µg g^{-1}	183 µg g^{-1}	267 µg g^{-1}
As	111 µg g^{-1}	172 µg g^{-1}	258 µg g^{-1}
In	134 µg g^{-1}	140 µg g^{-1}	144 µg g^{-1}
Pd	99 µg g^{-1}	126 µg g^{-1}	178 µg g^{-1}
V	13 µg g^{-1}	113 µg g^{-1}	187 µg g^{-1}
Li	35 µg g^{-1}	38 µg g^{-1}	40 µg g^{-1}

Table 2 continued

Element	Mass fraction min	Mass fraction average (n = 3)	Mass fraction max
Bi	16 µg g^{-1}	36 µg g^{-1}	54 µg g^{-1}
Nb	10 µg g^{-1}	28 µg g^{-1}	44 µg g^{-1}
Hf	18 µg g^{-1}	23 µg g^{-1}	28 µg g^{-1}
Pt	5 µg g^{-1}	13 µg g^{-1}	25 µg g^{-1}
Ge	4 µg g^{-1}	12 µg g^{-1}	20 µg g^{-1}
Sb	3 µg g^{-1}	8 µg g^{-1}	12 µg g^{-1}
Cd	0.6 µg g^{-1}	1.1 µg g^{-1}	1.7 µg g^{-1}
Be	< LOQ µg g^{-1}	0.6 µg g^{-1}	1.8 µg g^{-1}
Te	< LOQ µg g^{-1}	0.5 µg g^{-1}	1.5 µg g^{-1}
Rb	0.01 µg g^{-1}	0.48 µg g^{-1}	0.77 µg g^{-1}
Tl	< LOQ µg g^{-1}	0.33 µg g^{-1}	0.82 µg g^{-1}
Hg	< LOQ µg g^{-1}	0.15 µg g^{-1}	0.34 µg g^{-1}

ESI Table 3: *Range of total amount of each element measured in PCB from different smartphone manufacturers (n = 3) from averaged triplicates. 'Min' corresponds to the lowest determined total amount in PCB from three smartphones. 'Max' corresponds to the highest determined total amount in PCB from three smartphones. Data is sorted by mass fraction of element in PCB, see ESI Table 2 (see also Figure 3.2). Values are given in three significant numbers of digits (with maximum 5 significant numbers of digits after the decimal point for values < 1 mg).*

Element	**Amount min / g**	**Amount average (n = 3) / g**	**Amount max / g**
Cu	3.76	6.50	11.2
Fe	0.429	1.81	3.08
Si	0.730	0.915	1.03
Ni	0.504	1.03	1.89
Sn	0.385	0.599	0.949
Zn	0.0458	0.562	1.57
Ba	0.219	0.304	0.461
Al	0.130	0.277	0.394
Cr	0.0015	0.176	0.512
Ca	0.115	0.152	0.190
Ti	0.0784	0.110	0.166
Mn	0.0108	0.0336	0.0606
Ta	0.0248	0.0373	0.0530
Mg	0.00852	0.0248	0.0454
W	0.0105	0.0212	0.0397
Au	0.0125	0.0151	0.0173
Zr	0.00841	0.0162	0.0291
REE	0.00664	0.0114	0.0141
Pb	0.00344	0.00816	0.0136
Co	0.00609	0.00633	0.00666
Na	0.00496	0.00628	0.00889
Ag	0.00378	0.00576	0.00830
Sr	0.00285	0.00492	0.00847
Mo	0.00171	0.00264	0.00326
Ga	0.00219	0.00260	0.00327
As	0.00176	0.00249	0.00317
In	0.00165	0.00221	0.00327
Pd	0.00120	0.00189	0.00228

Table 3 continued

Element	**Amount min / g**	**Amount average (*n* = 3) / g**	**Amount max / g**
V	0.00029	0.00143	0.00229
Li	0.00043	0.00059	0.00084
Bi	0.00035	0.00049	0.00065
Nb	0.00022	0.00038	0.00054
Hf	0.00022	0.00038	0.00064
Pt	0.00009	0.00017	0.00031
Ge	0.00009	0.00016	0.00025
Sb	0.00007	0.00011	0.00015
Cd	0.00001	0.00002	0.00002
Be	< LOQ	0.00001	0.00002
Te	< *LOQ*	0.00001	0.00003
Rb	< 0.00001	0.00001	0.00002
Tl	< LOQ	0.00001	0.00001
Hg	< *LOQ*	< 0.00001	< 0.00001

ESI Table 4: *Mass fractions of measured elements in entire PCB from different smartphone manufacturer (n = 3) in µg g^{-1} (see also Figure 3.1). Entire PCB comprises triplicate from PCB of each smartphone plus separately measured metal covers and contacts which were mounted on PCB. Uncertainties (u_c) correspond to total combined uncertainties with a coverage factor of k = 1. In the last rows, the number of elements > LOQ and the Loss on Ignition (w/w) are given*.

	Smartphone I		Smartphone II		Smartphone III	
Element	**Mass fraction (*n* = 3)**	u_c	**Mass fraction (*n* = 3)**	u_c	**Mass fraction (*n* = 3)**	u_c
Ag	0.43 mg g^{-1}	0.15 mg g^{-1}	0.37 mg g^{-1}	0.09 mg g^{-1}	0.31 mg g^{-1}	0.07 mg g^{-1}
Al	25.2 mg g^{-1}	0.7 mg g^{-1}	17.3 mg g^{-1}	0.5 mg g^{-1}	10.6 mg g^{-1}	2.8 mg g^{-1}
As	145 µg g^{-1}	9 µg g^{-1}	111 µg g^{-1}	6 µg g^{-1}	258 µg g^{-1}	39 µg g^{-1}
Au	1.28 mg g^{-1}	0.09 mg g^{-1}	552 µg g^{-1}	37 µg g^{-1}	1.41 mg g^{-1}	0.14 mg g^{-1}
Ba	18.0 mg g^{-1}	0.7 mg g^{-1}	20.3 mg g^{-1}	0.9 mg g^{-1}	19.0 mg g^{-1}	1.9 mg g^{-1}
Be	1.8 µg g^{-1}	0.4 µg g^{-1}	< LOQ		0.8 µg g^{-1}	0.2 µg g^{-1}
Bi	53.8 µg g^{-1}	2.1 µg g^{-1}	15.5 µg g^{-1}	0.5 µg g^{-1}	39 µg g^{-1}	14 µg g^{-1}
Ca	9.48 mg g^{-1}	0.16 mg g^{-1}	8.34 mg g^{-1}	0.20 mg g^{-1}	12.3 mg g^{-1}	2.7 mg g^{-1}
Cd	1.7 µg g^{-1}	0.6 µg g^{-1}	0.9 µg g^{-1}	0.5 µg g^{-1}	0.6 µg g^{-1}	0.4 µg g^{-1}
Co	0.50 mg g^{-1}	0.20 mg g^{-1}	0.27 mg g^{-1}	0.13 mg g^{-1}	0.54 mg g^{-1}	0.14 mg g^{-1}
Cr	123 µg g^{-1}	5 µg g^{-1}	0.65 mg g^{-1}	0.18 mg g^{-1}	42 mg g^{-1}	7 mg g^{-1}
Cu	371 mg g^{-1}	9 mg g^{-1}	494 mg g^{-1}	10 mg g^{-1}	306 mg g^{-1}	26 mg g^{-1}
Fe	157.2 mg g^{-1}	3.2 mg g^{-1}	18.9 mg g^{-1}	1.0 mg g^{-1}	251 mg g^{-1}	24 mg g^{-1}
Ga	180 µg g^{-1}	21 µg g^{-1}	103 µg g^{-1}	12 µg g^{-1}	267 µg g^{-1}	37 µg g^{-1}
Ge	12.4 µg g^{-1}	3.2 µg g^{-1}	3.9 µg g^{-1}	1.2 µg g^{-1}	20 µg g^{-1}	6 µg g^{-1}
Hf	17.9 µg g^{-1}	1.5 µg g^{-1}	28.2 µg g^{-1}	2.0 µg g^{-1}	23 µg g^{-1}	4 µg g^{-1}
Hg	< LOQ		< LOQ		0.34 µg g^{-1}	0.29 µg g^{-1}
In	141 µg g^{-1}	10 µg g^{-1}	144 µg g^{-1}	11 µg g^{-1}	134 µg g^{-1}	52 µg g^{-1}
Li	35.2 µg g^{-1}	1.1 µg g^{-1}	36.9 µg g^{-1}	0.8 µg g^{-1}	40.5 µg g^{-1}	1.7 µg g^{-1}
Mg	0.701 mg g^{-1}	0.018 mg g^{-}	2.00 mg g^{-1}	0.05 mg g^{-1}	1.68 mg g^{-1}	0.32 mg g^{-1}
Mn	2.407 mg g^{-1}	0.037 mg g^{-}	0.48 mg g^{-1}	0.07 mg g^{-1}	4.9 mg g^{-1}	0.5 mg g^{-1}
Mo	244 µg g^{-1}	28 µg g^{-1}	75 µg g^{-1}	10 µg g^{-1}	265 µg g^{-1}	35 µg g^{-1}
Na	412 µg g^{-1}	27 µg g^{-1}	391 µg g^{-1}	35 µg g^{-1}	0.40 mg g^{-1}	0.20 mg g^{-1}
Nb	44 µg g^{-1}	19 µg g^{-1}	9.5 µg g^{-1}	1.6 µg g^{-1}	32 µg g^{-1}	8 µg g^{-1}
Ni	41.5 mg g^{-1}	1.8mg g^{-1}	82.9 mg g^{-1}	2.8 mg g^{-1}	57 mg g^{-1}	10 mg g^{-1}
Pb	283 µg g^{-1}	16 µg g^{-1}	597 µg g^{-1}	22 µg g^{-1}	0.61 mg g^{-1}	0.16 mg g^{-1}

Table 4 continued

	Smartphone I		Smartphone II		Smartphone III	
Element	**Mass fraction (*n* = 3)**	***u*c**	**Mass fraction (*n* = 3)**	**uc**	**Mass fraction (*n* = 3)**	***u*c**
Pd	99 µg g-1	5 µg g-1	100 µg g-1	4 µg g-1	178 µg g-1	19 µg g-1
Pt	7.3 µg g-1	1.1 µg g-1	5.3 µg g-1	1.2 µg g-1	25 µg g-1	5 µg g-1
Rb	0.8 µg g-1	0.3 µg g-1	0.7 µg g-1	0.1 µg g-1	0.010 µg g-1	0.008 µg g-
Sb	12.2 µg g-1	1.6 µg g-1	3.16 µg g-1	1.36 µg g-1	9.8 µg g-1	5.9 µg g-1
Si	60.0 mg g-1	1.7 mg g-1	45.3 mg g-1	1.5 mg g-1	80.2 mg g-1	2.1 mg g-1
Sn	38.1 mg g-1	1.1 mg g-1	41.7 mg g-1	1.8 mg g-1	31.4 mg g-1	2.9 mg g-1
Sr	284 µg g-1	5 µg g-1	372 µg g-1	10 µg g-1	233 µg g-1	62 µg g-1
Ta	2.80 mg g-1	0.24mg g-1	2.33 mg g-1	0.07 mg g-1	2.0 mg g-1	0.7 mg g-1
Te	< LOQ		1.5 µg g-1	0.9 µg g-1	< LOQ	
Ti	6.45 mg g-1	0.26 mg g-	7.30 mg g-1	0.31 mg g-	7.1 mg g-1	0.5 mg g-1
Tl	< LOQ		0.2 µg g-1	0.1 µg g-1	0.8 µg g-1	0.5 µg g-1
V	140 µg g-1	9 µg g-1	12.8 µg g-1	0.7 µg g-1	187 µg g-1	30 µg g-1
W	1.11 mg g-1	0.10 mg g-	1.74 mg g-1	0.07 mg g-1	0.86 mg g-1	0.11 mg g-1
Zn	3.77 mg g-1	0.16 mg g-	69 mg g-1	5 mg g-1	5.6 mg g-1	1.0 mg g-1
Zr	692 µg g-1	28 µg g-1	1.28 mg g-1	0.05 µg g-1	0.91 mg g-1	0.13 mg g-
Ce	1.7 µg g-1	1.2 µg g-1	2.1 µg g-1	0.8 µg g-1	4.9 µg g-1	1.6 µg g-1
Dy	189 µg g-1	24 µg g-1	170 µg g-1	21 µg g-1	163 µg g-1	37 µg g-1
Er	0.2 µg g-1	0.05 µg g-1	4.1 µg g-1	0.5 µg g-1	1.55 µg g-1	0.22 µg g-1
Eu	1.16 µg g-1	0.15 µg g-1	1.38 µg g-1	0.18 µg g-1	1.03 µg g-1	0.12 µg g-1
Gd	<LOQ		<LOQ		0.7 µg g-1	0.3 µg g-1
Ho	27 µg g-1	16 µg g-1	27.0 µg g-1	3.3 µg g-1	61 µg g-1	16 µg g-1
La	4.6 µg g-1	2.3 µg g-1	2.9 µg g-1	0.5 µg g-1	6.3 µg g-1	1.3 µg g-1
Lu	5.3 µg g-1	0.9 µg g-1	0.04 µg g-1	0.01 µg g-1	47 ng g-1	12 ng g-1
Nd	0.26 mg g-1	0.07 mg g-1	26 µg g-1	28 µg g-1	0.79 mg g-1	0.31 mg g-1
Pr	<LOQ		<LOQ		0.07 mg g-1	0.05 mg g-1
Sc	11 µg g-1	5 µg g-1	17.0 µg g-1	2.7 µg g-1	12.4 µg g-1	2.5 µg g-1
Sm	0.7 µg g-1	0.7 µg g-1	0.6 µg g-1	0.7 µg g-1	4.1 µg g-1	2.1 µg g-1
Tb	1.06 µg g-1	0.36 µg g-1	61 ng g-1	32 ng g-1	0.8 µg g-1	0.4 µg g-1
Tm	0.05 µg g-1	0.02 µg g-1	25 ng g-1	5 ng g-1	46 ng g-1	10 ng g-1
Y	43 µg g-1	7 µg g-1	0.23 mg g-1	0.04 mg g-1	40 µg g-1	15 µg g-1

Yb	0.61 µg g^{-1}	0.22 µg g^{-1}	171 ng g^{-1}	30 ng g^{-1}	0.19 µg g^{-1}1	0.05 µg g^{-1}
Number of determined elements	52		54		56	
Loss on ignition at 550°C (w/w)* / %	11.4		11.2		8.6	

*Loss on Ignition (LOI) of the PCB at 550°C shows on average 9-11 % weight loss. 550°C is the standard temperature used to estimate loss of organic and inorganic carbon (Dean. 1974; Hoornweg & Bhada. Tat. 2012). Heavy in metals with low melting points can already oxidize at this temperature (e.g. In, Li, Sn, Pb) increasing the weight. LOI is used as an indication for plastics components.

Literature:

W.E. Dean. 1974. J Sediment Petrol 44: 242-248

D. Hoornweg. P. Bhada-Tata. 2012. What a Waste: A Global Review of Solid Waste Management. Urban development series; knowledge papers no. 15. World Bank. Washington. DC.

ESI Table 5: *Range of total metal amount in entire PCB from smartphone manufacturers (n = 3) in g (see also Figure 3.2). Uncertainties (u_c) correspond to total combined uncertainties (k = 1). Total weight of measured elements, weight of the PCB and the relative mass fraction are given in the last rows*.

Element	Smartphone I		Smartphone II		Smartphone III	
	Total amount (n = 3) / g	u_c /g	Total amount (n = 3) / g	u_c / g	Total amount (n = 3) / g	u_c / g
Ag	0.0052	0.0018	0.0083	0.0021	0.0037	0.0008
Al	0.305	0.009	0.394	0.011	0.130	0.033
As	0.00176	0.00011	0.00254	0.00014	0.0031	0.0005
Au	0.0156	0.0011	0.0125	0.0009	0.0173	0.0018
Ba	0.219	0.009	0.460	0.020	0.233	0.023
Be	0.00002	0.00001	< LOQ		0.00001	< 0.00001
Bi	0.00065	0.00003	0.00035	0.00001	0.00048	0.00017
Ca	0.1152	0.0019	0.1898	0.0046	0.150	0.033
Cd	0.00002	0.00001	0.00002	0.00001	< 0.00001	< 0.00001
Co	0.0061	0.0024	0.0062	0.0030	0.0067	0.0017
Cr	0.00150	0.00006	0.0149	0.0041	0.51	0.09
Cu	4.51	0.11	11.24	0.22	3.75	0.32
Fe	1.910	0.039	0.429	0.022	3.08	0.30
Ga	0.00219	0.00026	0.00234	0.00028	0.0033	0.0005
Ge	0.00015	0.00004	0.00009	0.00003	0.00025	0.00007
Hf	0.00021	0.00002	0.00064	0.00004	0.00027	0.00005
Hg	< LOQ		< 0.00001	< 0.00001	< 0.00001	< 0.00001
In	0.00171	0.00012	0.00327	0.00024	0.00165	0.00064
Li	0.00043	0.00001	0.00084	0.00002	0.00050	0.00002
Mg	0.00852	0.00022	0.0454	0.0011	0.021	0.0040
Mn	0.0293	0.0005	0.0108	0.0015	0.061	0.007
Mo	0.00297	0.00034	0.00171	0.00023	0.0032	0.0004
Na	0.00500	0.00032	0.0089	0.0008	0.0049	0.0024
Nb	0.00054	0.00023	0.00022	0.00004	0.00039	0.00010
Ni	0.504	0.021	1.887	0.065	0.69	0.12
Pb	0.00344	0.00019	0.0136	0.0005	0.0074	0.0019
Pd	0.00120	0.00005	0.00228	0.00010	0.00218	0.00023
Pt	0.00009	0.00001	0.00019	0.00003	0.00031	0.00006

Table 5 continued

Element	Smartphone I		Smartphone II		Smartphone III	
	Total amount (n= 3) / g	**u_c /g**	**Total amount (n= 3) / g**	**u_c / g**	**Total amount (n= 3) / g**	**u_c / g**
Rb	0.00001	< 0.00001	0.00002	< 0.00001	< 0.00001	< 0.00001
Sb	0.00015	0.00002	0.00007	0.00003	0.00012	0.00007
Si	0.730	0.021	1.031	0.033	0.984	0.025
Sn	0.462	0.014	0.949	0.040	0.38	0.036
Sr	0.00345	0.00006	0.00847	0.00023	0.0029	0.0008
Ta	0.0341	0.0029	0.0530	0.0016	0.024	0.009
Te	< LOQ		0.00003	0.00002	< LOQ	
Ti	0.0784	0.0032	0.1658	0.0071	0.087	0.007
Tl	< LOQ		< 0.00001	< 0.00001	< 0.00001	< 0.00001
V	0.00170	0.00011	0.00029	0.00002	0.00229	0.00037
W	0.0135	0.0013	0.0397	0.0016	0.0105	0.0014
Zn	0.0458	0.0020	1.57	0.10	0.0687	0.0129
Zr	0.00841	0.00034	0.0291	0.0010	0.0111	0.0016
REE	0.0067	0.0009	0.0110	0.0014	0.0140	0.0097
Sum weight of elements /g	9.03667		18.59945		10.28331	
Weight of entire PCB /g	12.15242 ± 0.00001		22.75713 ± 0.00001		12.26893 ±0.00001	
Metal fraction of total PCB /%	74		82		84	

ESI Table 6: *Within model variability and within device variability of the total amounts of elements determined in PCBs (without metal covers and contacts) from model Smartphone I. Data with relative standard deviation (RSD).*

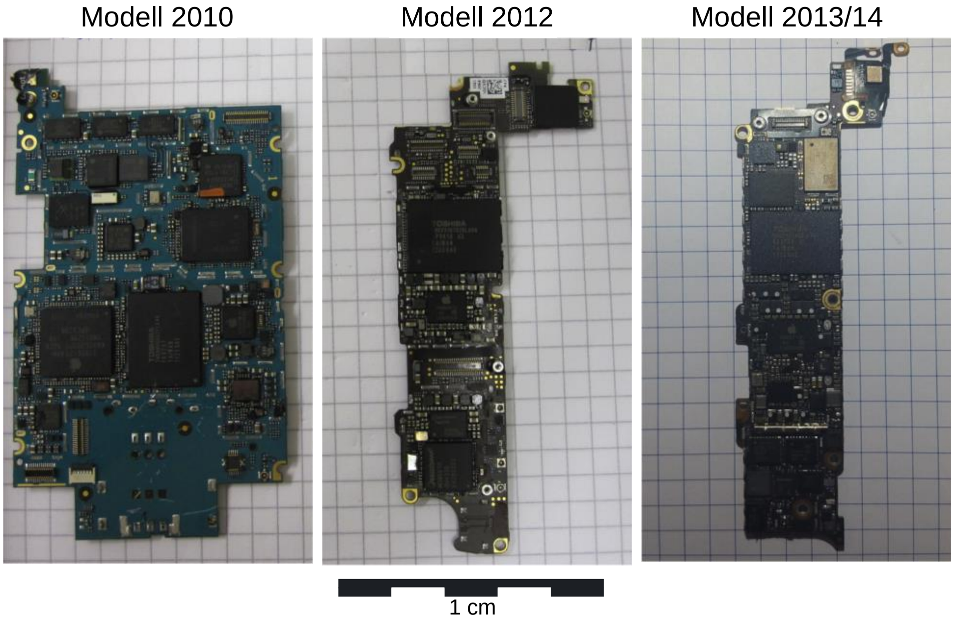
Element	Smartphone I (average from a, b, c)		Smartphone Ia		Smartphone Ib		Smartphone Ic	
	average (*n*=3) / g	RSD / %	average (*n*=3) / g	RSD / %	average (*n*=3) / g	RSD / %	average (*n*=3) /g	RSD / %
Ag	0.0050	16	0.0052	44	0.0041	35	0.0056	24
Al	0.306	22	0.353	2	0.336	2	0.228	2
As	0.0017	26	0.0019	6	0.00119	3	0.00204	2
Au	0.0147	3	0.0146	11	0.0144	6	0.01517	2
Ba	0.219	5	0.229	2	0.218	3	0.2089	1
Be	0.00002	7	0.00002	15	0.00002	10	0.00002	39
Bi	0.00065	5	0.00067	0	0.00062	3	0.00068	5
Ca	0.115	4	0.1153	1	0.1201	2	0.1100	1
Cd	0.00001	3	0.00001	39	0.00001	29	0.00001	35
Co	0.0020	5	0.00195	10	0.0021	31	0.0019	76
Cr	0.00150	2	0.00154	5	0.00147	0	0.00148	6
Cu	4.30	6	4.08	3	4.235	1	4.58	3
Fe	0.267	6	0.286	2	0.2623	1	0.253	2
Ga	0.00154	24	0.00161	1	0.00114	5	0.00186	3
Ge	0.00013	5	0.00013	7	0.00012	26	0.00014	3
Hf	0.00021	4	0.00021	8	0.00022	3	0.00021	7
In	0.00167	2	0.001677	2	0.00164	2	0.00170	3
Li	0.00043	2	0.00042	3	0.00044	3	0.00043	3
Mg	0.009	24	0.00736	2	0.00727	3	0.01093	2
Mn	0.0035	4	0.00360	2	0.00361	1	0.00339	2
Mo	0.00124	7	0.00121	12	0.00134	3	0.00118	19
Na	0.00496	10	0.00553	6	0.00472	6	0.00465	5
Nb	0.00013	19	0.00013	26	0.00011	14	0.00016	59
Ni	0.3079	1	0.310	3	0.303	2	0.310	3
Pb	0.00335	6	0.00332	6	0.00317	3	0.00356	6
Pd	0.00116	1	0.00117	7	0.00115	2	0.00118	1
Pt	0.00009	6	0.00009	18	0.00009	18	0.00008	6
Rb	0.00001	23	0.00001	35	0.00001	43	0.00001	19

Table 6 continued

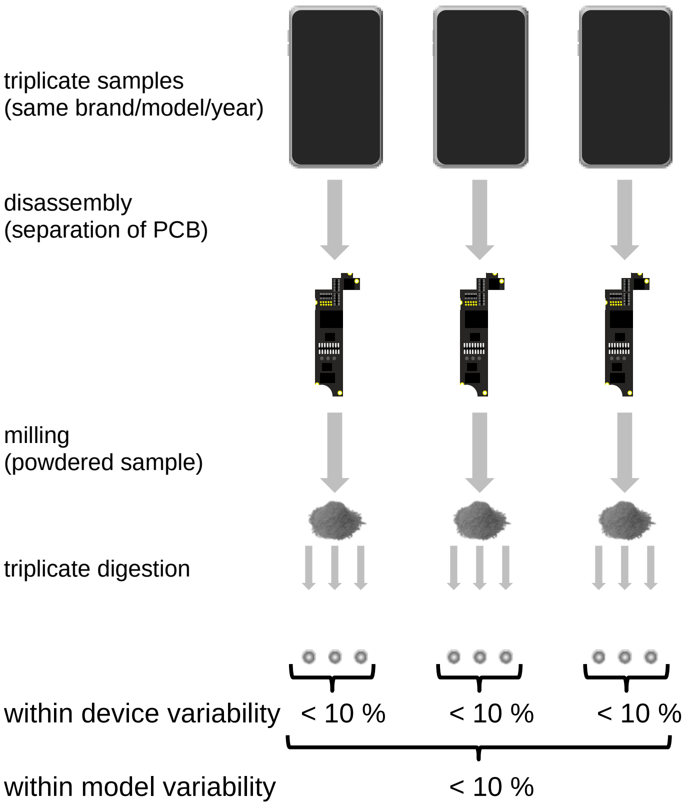
Element	**Smartphone I (average from a, b, c)**		**Smartphone Ia**		**Smartphone Ib**		**Smartphone Ic**	
	average (n = 3) / g	**RSD / %**	**average (n = 3) / g**	**RSD / %**	**average (n = 3) / g**	**RSD / %**	**average (n = 3) / g**	**RSD / %**
Sb	0.00013	9	0.00014	7	0.00011	16	0.00013	16
Si	0.714	2	0.707	3	0.703	2	0.734	2
Sn	0.452	4	0.441	2	0.443	1	0.472	3
Sr	0.00345	2	0.00353	0	0.00340	2	0.00342	2
Ta	0.0337	10	0.038	19	0.0314	2	0.0320	2
Ti	0.0729	2	0.0739	2	0.0709	1	0.07366	2
V	0.00013	12	0.00013	7	0.00014	2	0.00011	4
W	0.0130	12	0.0136	6	0.0112	7	0.0142	15
Zn	0.0458	15	0.0524	9	0.0461	1	0.0388	2
Zr	0.00841	4	0.00805	1	0.00876	3	0.00841	3
REE	0.0067	16	0.0079	11	0.00629	6	0.0059	8
weight PCB* / g	9.82102	1	9.66088 ± 0.00001		9.86501 ± 0.00001		9.93718 ± 0.00001	

*PCB without metal covers and contacts

ESI Figure 1: *Comparison of PCB from consecutive smartphones models of the same brand. Between 2010 and 2012, resource efficiency and miniaturization of PCB is clearly visible. Since 2012, PCB design have not changed significantly. This underlines that we investigated a representative PCB of newer smartphone generations***.**



ESI Figure 2: Schematics of the procedure to investigate within-device and within-model variability**.**



4. Geoscientific and sustainability context of metallic elements in smartphones

Our technological advances heavily depend on the supply of metallic elements. There have been rapid advances in electronics and telecommunications over the past 20 years (see **chapter 1**), and among other products, the increasingly complex consumer electronics have contributed to an increase in both the number and supply of metallic elements needed to manufacture these devices.

This chapter provides geologic, economic and socio-ecologic background information on why smartphones in particular have been symbolized for many different issues implicated with specialty metallic elements and sustainability. The greater framework of the topic, set by circular economy concepts and the Sustainable Development Goals, is also provided. Hence, this chapter provides the empirical description for the implications metallic resources in smartphones can have, related to technology metals and sustainability. The focus lies on metallic elements important for smartphones, and the general social, economic and environmental impact smartphones can have due to their metallic content.

In order to maintain the resource focus of this thesis, the discussions in **chapters 4.1., 4.2,** and **4.3** center on the resource use, the extraction, and the recycling of the metallic elements for smartphones. A preliminary case study with the aim to combine the issues of extraction and recycling by creating a potential metal tracing in order to analytically determine the geographic origin of extraction and the identification of recycled material is described in **chapter 4.4**.

The summary of these discussions is provided with the publication in **chapter 5**. Due to the fact that the results were published in an international journal, where the currency is US Dollar, **appendix IV** provides the recycling value of the metals Au, Ag, Cu, Pd, and Pt in Euro, updated to current prices (August 2020).

4.1. “Critical” raw materials and technology metals

Many of the metallic elements have, besides smartphones, numerous different applications with partly long product lives. These include future and key technologies for modern societies, for de-carbonization and energy-related technologies such as mobility and urban concepts, energy storage, power to gas, efficiency and lightweight construction in automotive and aviation, additive manufacturing (3D printing) and digitization. To describe a number of specialty metallic elements, different terms have been used and will be discussed in the following.

In order to meet the growing global demand for future technologies, the term "criticality" for certain metallic elements has come into the public focus (EU Commission, 2017).

The term "**critical raw material**" refers to non-energy and non-agricultural raw materials, which are of high economic importance combined with supply risk (Bauer et al., 2011; NSTC, 2011). Supply risk is considered to arise from a combination of several factors, such as a high concentration of production in few countries, sometimes combined with poor country governance, a limited material substitutability, and poor end-of-life recycling rates (e.g., Erdman & Graedel, 2011; NSTC, 2011; Graedel et al., 2013; Lovik et al., 2018). The criticality term has been widely discussed, especially in the EU due to its heavy reliance on imports and the importance of raw materials for the European industry (Reuter et al., 2013; Gunn, 2014; EU Commission, 2017; Schrijvers et al., 2020), and with over 81 EU projects covering the topic (Lovik et al., 2018). The main factors for labeling materials "critical" include the availability and security of supply of the material, existence and availability of substitutes for the material, the consequences of shortages, and the strategic importance of a materials' applications (OECD, 2019). The criticality of materials changes over time in response to the availability, supply, demand, and uses of these metals (Bauer et al., 2011; OECD 2019). Thus, due to these changing parameters over time, the EU defines a list of critical raw materials every few years, last in 2020 (EU Commission, 2020b). In the USA, where the industry is equally dependent on raw materials' imports, the United States Geological Survey (USGS) analyzes this issue from their perspective and with similar aspects (USGS, 2017). Yet, it needs to be noted that these lists vary depending on country viewpoint (e.g., the United States of America and the EU have different requirements for materials). The German Mineral Resources Agency (DERA) at the Federal Institute for Geosciences and Naturals Resources (BGR) defines mineral raw materials as being potentially critical if they have a high concentration of production and a high country risk, by also including country governance (DERA, 2019).

The term "**technology metal**" (Hagelüken & Meskers, 2010) for some of the specialty metallic elements for advanced technologies has also been used, although there is no excluding definition for the metallic elements stated under this term. Metallic elements usually included are gallium, germanium, indium, tantalum, and rare earth metals as they play a significant role in future technologies: eco innovations such as solar cells, electro mobility and wind turbines require similar "technology metals" and thus compete against each other due to their specific characteristics with little substitution options (Reuter et al., 2013; Hagelüken, 2014). Additionally, some of these metals are mined as by-products of other metals like copper, nickel or zinc and are thus limited by the production of the main metal (Frenzel et al., 2011); also, they are often produced in much lower quantities than base metals, making these smaller markets more sensitive to disruptions (Fizaine, 2013; Al Barazi, 2018).

The terms "rare metal" or "minor metals" are sometimes used to describe the lower production quantities and the minor occurrence of these mostly by-production metals in ore deposits, but are more of a conventional nature that is not strictly defined (Cox & Singer, 2011).

More comprising seems to be the term "technology critical elements" (Cobelo-Garcia et al., 2015), since it also covers industrial minerals (e.g., such as graphite, an important material for anodes in e-mobility batteries). This last term has only come up recently, and depending on context and literature, different terms prevail.

In this thesis, the focus will be on metallic elements only. For ease of terms, the label **technology metals** will be used for further discussions, encompassing all technology relevant metallic elements (metals, metalloids, and lanthanoids). **Appendix IIa** and **IIb** (total amount of measured elements, and mass fraction of measured elements in smartphones) show that smartphones as representative examples of WEEE contain all of the cited technology metals.

The criticality term will be avoided, as this would have to implement a far more complex investigation of different parameters (Bauer et al., 2011), and is country and time dependent; here, merely geological occurrence, global annual production, and importance of metallic elements for smartphones are investigated, enhanced by economic factors such as metal price and potentials for recycling, all of which are not country-specific; results are summarized in **chapter 5**.

In terms of criticality, from a geological point of view there are sufficient metallic elements in Earth's crust to provide supply for our growing demand (Gunn, 2014). However, it is a question of resource responsibility and ecologic thinking to use our resources in a sustainable, efficient manner. Also, price and supply risks pertain and volatile markets can affect industry in planning their production (DERA, 2019). Recycling can be a potential backup to shield these effects. Yet, primary mining will still be indispensable for the near future (Gunn, 2014).

4.2. Resource use: Circular economy and the Sustainable Development Goals

Two main initiatives currently top the policy agenda: the concept of a circular economy, and the UN Sustainable Development Goals (EU Commission, 2020a; UN, 2015). Both directly and indirectly address the growing demand for advanced resource use, which also specifically affect technology metals.

The circularity concept was first considered in the 1970s, e.g., as an "economy in loops" (Stahel & Reday, 1976). Since then the concept has been further adopted, the term “circular economy” was coined in 1990, and further adapted and promoted in the 2010s (Pearce & Turner, 1990; Ellen McArthur Foundation, 2013).

Circularity concepts propose to moving away from a linear "take, make, dispose" system to a circular approach by applying insights from natural ecosystems, to create a closed loop. The end of the product life cycle should be taken into account when selecting the materials for products, e.g., use of non-toxic, easy separable materials.

In a system of circular economy, attempts are made to minimize the depreciation of the raw materials used and at the same time to maximize the economic added value.

Several studies and initiatives for advancing circular economy have become central, especially in the EU (EU Commission, 2020a), but also globally, asking for a transition to better “design, make, and use things within planetary boundaries” (Ellen McArthur Foundation, 2013). Most importantly, the term circular economy covers not only recycling but encompasses a complete systemic thinking by including many interdisciplinary aspects such as consumer behavior, new business models for sharing and repairing, as well as resource efficiency, extending product life cycles, and adapting design for recycling, to name some key points (van Schaik & Reuter, 2014; Ellen McArthur Foundation, 2013). Design for recycling, i.e., the optimized accessibility of metals or compounds in complex multi-element composites, is an important concept that has already been discussed a few years earlier (e.g., Hagelüken & Corti, 2011). In the EU, the circular economy concept is part of the Green Deal, a set of policy initiatives with the overall goal to making Europe carbon neutral by 2050 (EU Commission, 2020a).

For the circular economy concept regarding recycling, the currently dominating yet limited materials centric view (e.g., recycling of copper, or gold) also needs to be broadened by a product centric view (e.g., the recycling of car parts, batteries, or magnets) to generate the best possible effects (Reuter et al., 2019). This could include rethinking the targeting (which materials) and the accounting (of economic models) of recycling.

Implementing circular economy goals can also (for most of the materials) give rise to a combination of secondary benefits, including reduced energy, consumption, waste, pollution, and costs, by increasing resource efficiency and promoting different consumer behaviour (Gaustard et al., 2018).

Almost simultaneously to circular economy advances, the Sustainable Development Goals (SDGs), adopted by all United Nations member states in 2015, arose into the public focus with 17 SDGs at its core: while many SDGs relate to resources (e.g., by water, climate and energy relations), SDG No 12 states responsible consumption and production patterns as a goal (UN, 2015).

The SDGs build on decades of work by countries and the UN, starting with the Earth Summit in Rio de Janeiro in 1992 which set the Agenda 21, the first comprehensive plan of action to build a global partnership for sustainable development to improve human lives and protect the environment (UN, 2020).

When attempting to combine these initiatives, the circular economy concept is an integral part of the sustainability agenda and can contribute to several different SDGs. Both aim towards a more sustainable world by respecting planetary boundaries.

In regards to the resource focus of this thesis, the SDGs tower over the entire agenda, while the circular economy aspects tighten the focus and are of greater direct connection, especially with recycling as an integral part of circular economy, as discussed in chapter 5.

Also, both initiatives, especially circular economy, mention technology metals and the importance of resource efficiency for a sustainable use (Ellen McArthur Foundation, 2013; UN, 2015; EU Commission, 2020a).

To determine the transfer towards a more sustainable world, different metrics have been developed as sustainability indicators to measure the sustainability of resource use. One indicator, resource productivity, is a measure of the total amount of materials directly used by an economy, measured as domestic material consumption (DMC) in relation to GDP (gross domestic product). Resource productivity (GDP/DMC) is the EU sustainable development indicator for policy evaluation, monitored by Eurostat (EUROSTAT, 2020). The OECD and UNEP also use GDP/DMC as one main indicator for their sustainability strategies (OECD, 2011; UNEP, 2011). Indicators of direct material flows derived from economy-wide material flow accounting are now routinely reported by all EU member states and collected by EUROSTAT (EUROSTAT, 2020). The material footprint (MF) can be regarded as a further development of the DMC for optimizing resource productivity assessment, by additionally including the upstream resource requirements of traded goods (Wiedmann et al., 2013; Giljum et al., 2014). For enhanced analyzation of the environmental performance of European countries in their global context, the EXOBIASE database has been developed (Tukker et al., 2014) with an extensive global dataset. Here, for example the inequality of global resource consumption is one outcome (Tukker et al., 2014) and will be further addresses in **chapter 4.3**.

These assessment methods are based on aggregated data and are usually used for sector analysis (e.g., agriculture sector) at national or global level, and the transformation over time. Thus, these assessments provide important data mainly applicable for industrial ecology topics and statistical calculations.

For environmental impacts, other methods such as the ecological rucksack have been termed as another possible approach. In 2012, the ecological rucksack for a mobile phone (not smartphone) was calculated with 75.3 kg (Nordmann et al., 2014). However, this calculation used estimated general mobile phone content only, and was based on the commercial database Ecoinvent, which is too aggregated to provide values for single materials and does not provide a detailed geoscientific context.

Therefore, for this thesis, a different material centric approach was needed to apply a more detailed geological context. The aim was to calculate the direct raw materials input of all metals required to produce a smartphone, without addressing trade data such as transport, production facilities or such. Ultimately, the calculation should show the weight of all ores essential for the production of the metallic elements for the production of a smartphone, compared to the end weight of a smartphone. To achieve this goal, widespread research on the range of each metals` ore grades in current mines was conducted and added together according to their content in smartphones. The results are shown in **chapter 5.8** and in **appendix III**: 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.

It needs to be noted that this is just an absolute weight calculation of ore and host rock for the extracted metals of smartphones; it cannot necessarily be used as an indicator for, e.g., CO_2 usage or energy demand, as for these determinations different calculations must be included for each metal individually. The example of copper shows that due to technical developments, the processing of on average lower ore contents in mining did not generally lead to an increase in greenhouse gas emissions (per kilogram of copper-metal; see Rötzer & Schmidt, 2020). However, this would have to be examined for each metal and for each host-rock regarding other by-products separately and will surely reveal different outcomes for the metals. Nelen et al. (2014) suggested that the recovery of precious metals such as palladium from an environmental point of view should be prioritized over mass-related aspects for recycling.

Generally, the detailed smartphone content from this thesis could be used for an updated ecological rucksack calculation, or for a product specific case study of the material footprint of smartphones.

Life Cycle Assessments (LCA) are another framework that can be used for calculating the sustainability impact: this approach allows the modelling of complex material flows and exemplifies environmental impacts potentially associated with each material flow (EU Commission, 2012). LCAs of mobile phones show that the raw materials consumption for production of the devices has the highest impact (Tanskanen, 2013; Teehan & Kandlikar, 2014). Thus, a prolonged use phase is the most sustainable way for smartphones. Yet, very often not anticipated in these assessments are the raw materials for the infrastructure that are needed to support smartphones.

This infrastructure comprise the mobile phone network (transmitting towers, masts, etc.), and to some extent also the internet (i.e., the servers, which is a network of networks, both commercial and private): both require large amounts of energy and raw materials. Although the infrastructure and its raw material use will not be further investigated in this thesis, they are crucial for smartphone usage and should not be disregarded. The internet cannot be separately investigated for smartphones due to their shared usage with laptop and desktops. Thus, only a brief overview of mobile networks and their impact are given in the following.

4.2.1. Resource use of smartphone infrastructure

The first phone call was made using just one phone mast and the short call was made locally. Before mobile phones could be successfully marketed to the public (see **chapter 1**), a mobile phone network (transmission equipment, feeders, antennas, masts, etc.) needed to be developed and deployed. Towers and masts come in many shapes, currently steel lattices are the most common. Deployment times and network standards vary from country to country, yet roughly every ten years a new standard was deployed, starting with the first generation (1G) network as an analogue system in the late 1970s, early 1980s. The second generation (2G, or GSM (Global System for Mobile Communications) cellular network was developed at the end of the 1980s, early 1990s. This digital network was primarily optimized for voice telephony and over time was expanded to include data communications (Hardman S & Steinberger-Wilckens R, 2014; ITU, 2019). The third generation network (3G) is an UMTS standard (Universal Mobile Telecommunications System) with digital cellular telephony including video telephony, based on the GSM-standard, and was developed in the late 1990s and became deployed in the 2000s. The fourth generation (4G) LTE (long term evolution) standard became commercial in the late 2000s, early 2010s. The fifth generation (5G) network is currently being tested and developed (ITU, 2019).

Each generation change is characterized by new frequency bands (e.g., 800-900 MHz for 3G), and different bandwidth (often referred to as download speed; e.g., 2G network can carry 0.1 Mbit/s (megabits per second), while 5G target a download speed of 1,000-10,000 Mbit/s technology) (ITU, 2020). This means that the subsequent built up of infrastructure was and is needed, meaning the placement of different metals for the infrastructure at high costs. Sharing of cellular infrastructure has become regulated in some countries to lower the impact (see ITU 2020). 5G networks will require much more sophisticated antennas and transmission equipment (e.g., with semiconductor materials such as gallium nitride and indium phosphide for high frequency powers (Argus metals, 2019)), and transmitters need to be in closer intervals due to higher frequencies (shorter wavelengths) which is due to the fact that other frequencies are already blocked by 2G, 3G and 4G. Although 5G antennas and base stations are physically much smaller in size (called small cells) than those for 4G, and many new models for smaller poles are being developed, yet many more small cells will be needed to cover the desired areas. Thus, the new digital infrastructure and fast, high capacity networks for a whole new generation of applications and industrial advance with the new 5G standard will require not only updated and compatible smartphones and other devices, but also a many other raw materials to set up the infrastructure (ITU, 2019; ITU 2020). Summarizing, although the raw material content for the future infrastructure cannot be depicted here in detail, there will be many more raw materials needed to set up these networks.

4.3. Extraction and recycling

One demanding issue related to raw materials in general and technology metals in specific has been shown in several studies: the imbalance between emerging countries of the global South and the consuming developed countries of the global North (e.g., Tukker et al., 2014; Ritchie et al., 2018). This imbalance, specified here again with a raw materials focus, especially occurs on both ends of the value chain: Raw materials extraction with all related social and ecologic issues takes place mostly in emerging countries (Tukker et al., 2014; Izatt, 2016), and post-consumer products and packaging often end up in these countries (OECD, 2019). Yet, the use phase of these characteristically high-tech-products in between those ends typically takes place in the developed countries (ITU, 2016; Huisman et al., 2017).

At the beginning of the life cycle, many of the developed nations are dependent on reliable, stable imports of technology metals for production (Bauer et al., 2011; NSTC, 2016; DERA, 2019). High labour costs, high environmental standards and an arising negative reputation of extraction and mining in developed society are some of the high hurdles for new mining projects in developed countries (Dold, 2009; Izatt, 2016). The often negative issues related to extraction, such as CO_2-emissions and other environmental and social impacts, are left to the producing countries and are as of yet clearly not covered by commodity prices (Huisman et al., 2017; OECD, 2019).

At the end of the life cycle, large quantities of WEEE are generated in developed countries, yet are processed by the informal recycling sector in developing nations (Huisman et al., 2017). Despite the existence of waste shipment regulations intended to prevent international trade of, e.g., waste mobile phones (non-functioning devices that are not economically refurbishable), some WEEE generated in OECD nations is still illegally exported to the informal recycling sector under the guise of reuse (OECD, 2010).

The SDGs and the circular economy concept seek (among other issues) to address these inequalities at both ends of the value chain.

Recycling could be one supporting aspect and will be further discussed in **chapter 4.3.2**. The issues at the beginning of the life cycle will be discussed in the following.

4.3.1. Extraction: Responsible sourcing and conflict minerals

Smartphones are frequently quoted when discussing sustainable sourcing and the so-called conflict minerals (e.g., Enough Project, 2009; EU Parliament, 2017). Transparency along the value chain and addressing the social and ecological issues at the beginning of the life cycle have become more and more important for producers and consumers. Media attention for negative effects of raw material extraction play an increasingly important role in this context with mobile phones, e.g., the documentary movie “Blood in the Mobile” (Poulsen, 2009) and the Amnesty report on cobalt (Amnesty International, 2016) attracted wide media attention, with the term conflict minerals catching the public focus. Despite various measures that have already entered into force there are still many challenges in implementing transparent value chains. In our globalized world, the supply chains are often complex with many subsidiaries and traders, which is why the producers do not always have all information of their stations in the value chain. There are special challenges in the downstream area of the supply chain, as to where raw materials come from and where they are processed. However, public knowledge of “conflict minerals” is limited or worse, faulty assumptions can lead to a demonization of entire raw materials and their production.

This chapter provides an overview of the problems and international laws and guidelines addressing the issues in the downstream section of the supply chain.

Minerals associated with violations against international laws, which are extracted from conflict zones, are referred to as “conflict minerals”, although this is not a strictly speaking definition. Especially well documented is the case in the Democratic Republic of the Congo (DRC), which is one of the most mineral-rich countries in the world. In relation to the DRC, the metals tin, tantalum, tungsten, and gold (often referred to as 3TG) and their ores are referred to as conflict minerals. Especially in the years 2000-2010, armed groups in eastern DRC demanded taxes, bribes or other payments for these extracted minerals. These minerals are traded on national and international markets, and ultimately find their way through complex supply chains into finished consumer and industrial products. The revenues from these minerals provided armed groups with financing to continue a conflict which indirectly supported torture and forced labour (EU Commission, 2014; RSN, 2020). These issues affects mainly the ASM sector (artisanal and small scale mining). Yet LSM (large scale mining) in the DRC, commonly facilitated by large international companies, has not been used for conflict financing (BGR, 2020). Tin from other sources such as Indonesia, or tantalum from Australia, are not related to the conflict label; the term is region specific.

Two legislations regarding due diligence and origin reporting have recently come into force to address the issue of conflict minerals:

Dodd-Frank Act, USA

With the Dodd Frank Wall Street Reform and Consumer Protection Act (Section 1502), in 2010 a federal law came into force for the USA that contains regulations for companies dealing with conflict minerals. Conflict minerals are the 3TG, originating in the DRC and the adjoining countries. As part of the disclosure requirements, companies must show whether the 3TG are used in their production process, and if this is the case, it must be proven whether the conflict minerals come from the DRC or its neighboring countries. If both criteria apply, the companies must comply with the reporting requirements, which include the preparation of an audited report ("Conflict Minerals Report") for the US Securities Exchange Commission with comprehensive information on the origin and use of the conflict minerals. The results of the disclosure and reporting requirements must be made publicly available by the companies on the Internet. Companies must meet the disclosure and reporting requirements under the Dodd-Frank Act for the first time by May 31, 2014. The Dodd Franc Act has not been strictly enforced since 2017 anymore, yet large high-tech companies still follow the complete procedures to prevent image damage.

EU Due Diligence Regulation

The EU Parliament decided to make it mandatory for EU-based importers to demonstrate due diligence when importing conflict minerals from conflict-affected and high-risk areas. Unlike the Dodd Frank Act, with its geographic focus in and around the DRC, the EU regulation has a global scope in order to avoid unintended negative consequences for producers in a given region.

The EU regulation on the due diligence obligations in the supply chain for importers of tin, tantalum, tungsten, their ores and gold from conflict and high-risk areas came into force on June 8, 2017. The EU regulation obliges EU importers of these raw materials to carry out a due diligence check along their supply chains. Due diligence implies supply chain controls in order to identify the risk of funding harmful activities, in line with OECD recommendations. Following the OECD Guidance, importers must comply with obligations concerning the management system (particularly traceability), risk management, third-party verification (e.g., external audits) and communication. Larger manufacturers must also inform how they comply with the requirements of the new regulation from the origin of the raw materials. Large companies with over 500 employees who buy tin, tantalum, tungsten and gold for use in their products will have to disclose their procurement practices in the future. Compliance with the due diligence requirements will be controlled by the authorities of the EU member states, with the exception of recycled minerals and very low import quantities (5 percent of all imports). Due diligence should apply starting January 21, 2021 (EU Commission 2017).

OECD Due Diligence Guidelines and other voluntary initiatives

Companies also have the opportunity to join voluntary initiatives for the sustainable and conflict-free use of raw materials. Such associations for dealing with conflict minerals exist both at country and company level as well as in the form of multi-stakeholder organizations, e.g., the OECD guidelines for responsible sourcing in the Great Lakes Region in and around the DRC, and the Tin Supply Chain Initiative (iTSCi).

The bottleneck at the intersection of up- and downstream supply chains are smelters and refiners for processing the minerals. For example, initiatives use auditing for due diligence as main tool, with defined standards for smelters and refiners for several minerals. Initiatives provide lists of smelters and refineries which participate in the Responsible Minerals Assurance Process (RMI, 2020). Many downstream players request their suppliers to demonstrate due diligence in these programs. Similarly, the EU regulation builds on the formal recognition of these external industry initiatives in order to improve efficiency and streamline work flows.

In 2006-2007, the BGR has developed the Certified Trading Chains (CTC) certification scheme. The main objective of the CTC scheme is to certify responsible mining practice or “ethical” production and trade of minerals, notably the 3TGs (but in principle open to other minerals as well). Importantly, the scheme acknowledges the specific challenges pertaining to the ASM sector and is hence particularly concerned with feasibility and impact in an artisanal context (BGR, 2020). CTC focuses on the mine site level (rather than the associated supply chain) and relies on independent 3rd party auditing as assurance mechanism. Since 2011, the scheme has been implemented in the DR Congo as part of the German-Congolese development cooperation. In this context, the BGR acts as an advisor to the DRC Ministry of Mines which established CTC as a national ASM standard and issues CTC certificates for compliant mine sites.

The Extractive Industries Transparency Initiative (EITI)

The EITI aims to improve transparency and governance of natural resources in the EITI countries around the world. EITI sets global standards for the good governance of oil, gas and mineral resources. The EITI Standard requires the disclosure of information along the extractive industry value chain, from how extraction rights are awarded, to how revenues make their way through the government and how they benefit the public (EITI, 2020).

Special examples tantalum and cobalt

Tantalum and cobalt are frequently cited when smartphones and sustainability issues arise (e.g., Amnesty International, 2016). Thus, specific background information on these two important elements is decribed in the following.

Tantalum

During the Dotcom Bust, tantalum, for its use in small high density capacitors in electronic devices such as laptops and mobile phones, demand and prices skyrocketed in the year 2000. “Coltan”, the ore from which tantalum is derived (coltan is the abbreviation of columbite-tantalite, with columbium being the original name for niobium, which usually occurs together with tantalum) became infamous in the media. The illegal taxation of tantalum mining and trade by local warmongers in the DRC has already been addressed by the UN in 2001 (UN, 2001) and IPIS in 2002, culminating in the public attentive movie report “Blood in the Mobile”, which directly accused mobile phones producers (Poulsen, 2010). Since 2010, comprehensive due diligence monitoring and traceability procedures have been established in the eastern DRC as well as in Rwanda, the two main global producers of tantalum. Both government control and industry initiatives have contributed to this improvement. Almost all global tantalum smelters are certified as compliant with the OECD due diligence recommendations. As a result, conflict financing risks from artisanal tantalum mining have been substantially reduced (BGR, 2020).

Cobalt

Although cobalt, an important component of Lithium-Ion-Batteries, has been extensively covered in the media for human rights violation, it is not termed a conflict mineral, i.e., it does not fall under the legislation of the Dodd Franc Act or the EU-regulation. For cobalt, as for all raw materials, the generally recommended due diligence of the OECD guidelines applies (OECD, 2011).

The DRC hosts approximately 50 % of the global cobalt reserves and contributes more than 60 % to global mine production (Al Barazi, 2018). Cobalt extraction is mainly through large-scale industrial mining, but ASM activities contribute a variable share of 10 – 25 % to national cobalt output. The characteristic features of artisanal small-scale mining are high manual labor, low capital requirements, little use of technology and little mechanization. Corresponding risks include unreliable work protection, among other issues. Reports specifically name child labour as serious offences (e.g., Amnesty International, 2016). However, not all artisanal mining cooperatives are illegal or offence human rights violation; they also provide a substantial part of livelihood and local work force with up to 200,000 individuals alone for cobalt in the DRC.

The intensity of small-scale mining varies with the development of raw material prices. Therefore, the artisanal sector also has an important function to shield short-term demand peaks. This was most recently the case during the cobalt price peak in 2018, in which artisanal mining expanded massively and generated up to 18% of cobalt's annual production. The commercial mining sector cannot react in such short timeframes.

Summarizing for cobalt and tantalum, it is apparent that there is no easy diminishing as not all cobalt or tantalum from conflicted areas are “bad”. Thus, demonizing the general use of tantalum or cobalt from the DRC, and only processing the ores from other countries deprives many people and their families of their living ground. However, many problems remain and need to be addressed systemically. New technologies and traceability approaches, such as the blockchain technology with a decentralized logging record, could support in finding a solution (e.g., RSBN).

4.3.2. Recycling: The solution to all problems?

Recycling is one key aspect important for this thesis to complement and minimize some of the described issues such as availability, demand, price volatility, and address sustainability in general. Recycled metals are generally termed sustainable, no matter where they originated in their previous use (EU Commission, 2020a). This makes the use, for example of recycled tantalum or cobalt favourable for companies (see previous section) to avoid negative press. The past years have then seen increased efforts for collection and recycling (Huisman et al., 2017).

Most of the technology metals have, besides smartphones, numerous different applications with partly long product lives. Different advances in technologies can impact the demand for metals in relatively short time spans (approximately 1-2 years), but the mining sector cannot react this fast. The mining industry is cyclical, due to the lag between investment decisions and new supply to be available (PWC, 2018). Investment into the mining sector is a risky business. At exploration stage it is not clear whether a project will successfully enter the next project stage such as the feasibility, construction and operation stages. At construction stage, a mining project might even be deferred due to new permit requirements, planning of infrastructure, gaining governmental and social support, escalating costs, etc. From exploration to mining, it can take about 10-15 years and millions or billions of US dollars to start production, depending on the type of commodity, the region where it is mined and the international market environment (Buchholz, personal statement). Considering the volatile markets for these materials, it is evident that mining of primary resources needs backup through other ways and means. Secondary sources from recycling can be one alternative (Gunn, 2014).

In terms of quality, many metals can be recycled any number of times (Chancerel et al., 2013). They are therefore needed and not consumed (for certain special alloys, however, only so-called downcycling can take place, e.g., for certain aluminum alloys). As with the primary raw materials, not only the metal contents investigated here play an important role in the recovery of secondary raw materials, but also various other factors. In addition to the problems regarding the return and the collection of old devices (accessibility, logistical effort, transport routes, etc.), there are also challenges within the separation processes and recycling technologies (Graedel et al., 2011; Chancerel et al., 2013). The value of the recovered metals (at the given metal and scrap prices) must support all processes for their extraction economically. Also, the physical and thermodynamic limits for recovery must be observed (i.e., which combined elements can be separated using pyro- and /or hydrometallurgical processes and which elements go into the slag and can only be extracted from here with increased energy expenditure (Reuter & van Schaik, 2012). In terms of the amount of energy used, recycling must therefore also be considered from an ecological perspective. In the case of indium for example, for certain products (e.g., from the recycling of LCD screens), secondary production is associated with higher greenhouse gas emissions than primary production (Rötzer & Schmidt, 2020). Thus, sometimes recycling of products can lead to a greater environmental impact (by separation, transport, pretreatment, energy and emissions) than can be saved through recovery. This means that 100 % recycling of all metals in a complex multi-metal matrix such as smartphones is technically and thermodynamically not feasible, economically not feasible, and ecologically not sensible (Reuter & van Schnaik, 2012; Hagelüken 2014; Reuter et al., 2019). Detailed data for each metal and product application is required. However, for some metals in certain applications, existing recycling schemes already make an important contribution to increasing the supply of raw materials and thus also their availability (Reuter et al., 2013). This applies for example to copper and aluminum (Graedel et al., 2011).

As of yet, recycling can only complement the primary supply from raw materials; the stock of secondary metals available through recycling will be insufficient to meet growing demand, even if recycling efficiency would be very high. This can be seen with a simple example for copper: In 1990, annual production for copper was 10 Mio tons. In 2019, annual production was 24 Mio tons (DERA, 2019). The higher demand for copper today cannot be met even if recycling was 100 %. Especially when considering that copper in modern society has an average use time of approximately 50 years (Mudd et al., 2012), and most of the copper is still in use in bridges, cars, buildings, etc., it is clear that secondary raw materials from recycling are important, yet can only partly relieve some issues of supply, sustainability and price volatility.

Recycling of WEEE and smartphones in particular

As stated in **chapter 1.2**, WEEE is the world's fastest-growing domestic waste stream. Reasons are, among others, the high consumption rates of EEE, short life cycles, and few options for repair (Forti et al., 2020).

In 2019, a record 53.6 million tons of WEEE was recorded globally. Estimations show that the amount could rise to around 75 million tons by 2030, a then doubling of the amount in 16 years (Forti et al., 2020). Globally, Europe ranks first in terms of WEEE-generation per capita with 16.2 kg, followed by Oceania (16.1 kg), the Americas (13.3 kg), Asia (5.6 kg) and Africa (2.5 kg). At the same time, Europe is also the continent with the highest collection and recycling rate (42.5 %), followed by Asia (11.7 %), the Americas (9.4 %), Oceania (8.8 %), and Africa (0.9 %; Forti et al., 2020).

Globally, only 17.4 percent of WEEE was collected and recycled in 2019. This leaves 82.6 % unaccounted for. Around 7-20 % of the total WEEE are estimated to be exported as second-hand products or (illegal) WEEE and 8% are discarded into waste bins in high-income countries (Forti et al., 2020).

Although a (legal) second or third use phase for smartphones is highly beneficial in terms of resource efficiency as a longer use phase is more sustainable (see **chapter 4.2**), it depends on where the prolonged use takes place. Many second-life devices are used in poorer countries. Yet, a lack of appropriate recycling at the end diminishes the previous advantage. This is a major challenge especially in developing countries where, on the one hand, access to smart devices is of high interest for development, yet recycling infrastructures are problematic. In middle- and low-income countries, the WEEE management infrastructure is managed mostly by the informal sector under substandard conditions, which can cause severe health effects to workers and surroundings. In India, for example, 95 percent of WEEE is collected by the informal sector and ensures the livelihood of many people (Forti et al., 2020). However, efficiency of informal recycling is low compared to large scale industrial recycling processes, with losses of 30 % and more, and toxic content is not disposed of properly. The pressing issue remains on how to establish a cooperation between the informal and the formal sectors so that the equipment is ultimately recycled accordingly and, yet people from the informal sector still have an income.

Smartphone recycling in developed countries varies slightly. Most common recycling facilities concentrate on the metals Au, Ag, Cu, Pd, and Pt, as they yield the most value, are fairly easy to extract with a copper melt, and have recovery efficiencies at approximately 93-98 % (Hagelüken, 2014; Nordmann et al., 2014). Collected smartphones are pre-treated (removing of the battery) and often, only the dismantled printed circuit boards arrive at the smelting facilities. A ton of PCB, sold to the smelter facilities, yields more profit than a ton of untreated smartphones (without batteries). Also, PCB from computer, laptops and smartphones are collected and treated together. The devices or the PCB will then be shredded, sorted (magnetic, lighter plastics and non-magnetic metallic fraction) and melted in a smelter or furnace. In most facilities, the plastics from smartphones function as reduction agent that also produce direct energy for the furnace. There are only three facilities in Europe (Umicore AG in Belgium, Aurubis AG in Germany, and Boliden in Sweden) that are able to recover more elements from smartphones and WEEE via integrated processes, combining hydro- and pyrometallurgic processes. These advanced facilities are capable of recovering up to 17 elements in total, such as In, Ni, Pb, Se, Sn, yet with revenues at around 50-80 % recovery, dependin on the element (Nordmann et al., 2014).

Chapter 5 presents detailed results which additional metallic elements could potentially be recycled from smartphones. For better comparison and updated with new prices, metal values are also given in Euro in **appendix IV**, which supplements **Figure 5.4** (chapter 5 summarizes the results in US Dollar, as this is the main currency for raw materials).

4.4. Metal tracing: platinum isotope analysis

The investigation of the isotopic composition of metals in smartphone represents an additional aspect addressed in this thesis. Both the tracking of devices for metal origin at the beginning and for monitoring of recycling at the end of the value chain have important social, ecologic and economic reasons (sees **chapters 1.2** and **4.3**).

Whilst the latter, the monitoring of WEEE, is in particular of interest to ensure safe ecologic and economic treatment of waste, it also has a large social component. Smartphones in specific, next to personal computers, were termed as one of the main WEEE devices to illegally land on waste dumps in countries of the global South for small scale recovery of metallic elements by poorly equipped people (Basel Convention, 2012). However, the issue of WEEE monitoring has been and can only be facilitated by larger projects, some by using tracking transmitters implanted in larger devices. For example, radio frequency identification (RFID) tags have been used in the WEEE Trace project, to monitor waste management techniques for different appliances (WEEE Trace, 2015). Whilst WEEE tracking is important, this thesis aimed to address the raw material tracing: at the beginning of the value chain when it comes to backtracing the origin of raw materials, and possibly even at the end of the value chain, to provide proof if recycled material has been used.

Transparency along the value chain and addressing the social and ecological issues of the beginning of the life cycle has become more and more important for producers and consumers in the last decade. Media attention for possible negative effects of production along the supply chains play an increasingly important role in this context, e.g., triggered by the Amnesty report on cobalt (Amnesty International, 2016). Especially tantalum and its ore “coltan” became the infamous raw material for financing warfare and human rights violations (Nathan and Sarkar, 2011). Tantalum is one of the conflict minerals (see chapter 4.3 for more details); it usually occurs with the element niobium and “coltan” is the name derived from the ore columbite-tantalite (columbium is the original name for niobium). A tracing of origin for tantalum ores was developed and has since been established by Melcher et al., 2008. This method developed a distinctive geochemical, geochronological, and mineralogical signature of individual production sites using multiple laboratory methods, requiring sophisticated and extensive sample preparation and laboratory analytical procedures, which include complete analysis of sample by several techniques including rock X-ray florescence (XRF), X-ray diffractometry (XRD), ICP-MS, ICP-OES, electron microprobe, U-Pb dating, and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). This method was developed to address the issue directly with the tantalum ores, before they are treated in the smelters for further refinery. No tracing of tantalum to the origin is possible once it exits the refinery process and is implemented in products. Tantalum used from secondary sources (i.e., recycled tantalum) is generally termed “conflict-free”. Whilst this terming can be criticized, it is not possible to (analytically) determine whether the used tantalum originated from a secondary source or from a primary source.

To combine these two ends of the value chain, one aim of this thesis was to elaborate on the possibility to trace one metallic element back to the initial resource, and potentially even distinguish recycled material from original metal material by isotope analysis.

For this to be feasible, a metal with as few as possible resource provinces would be needed. Platinum Group Elements (PGE) – platinum, palladium, rhodium, ruthenium, iridium, and osmium - are mainly sourced from three general areas worldwide. Up to 90% of PGEs are produced in South Africa, Russia, and North America (Oberthuer, 2016). South Africa alone hosts 70% of the world’s PGE resources (Tredoux et al., 2009), mainly in the two most significant known platinum group mineral-bearing orebodies in the world: the Bushveld Complex in South Africa and, to a lesser extent, in the Great Dyke in Zimbabwe. Additional to the relatively few geographic occurrences, Pt has other features that could be viable for istopic provenance.

Platinum (Pt) has six naturally occurring isotopes (^{190}Pt, ^{192}Pt, ^{194}Pt, ^{195}Pt, ^{196}Pt and ^{198}Pt). The relatively large mass difference (2%) between the abundant heavy and light isotopes of Pt, coupled with its variable redox states in the Earth’s core, mantle and surficial environments (Pt^0, Pt^{2+} and Pt^{4+}), and the large differences in Pt abundances that characterise Earth’s major geochemical reservoirs suggest that Pt could underlie significant stable isotope variations (Creech et al., 2014). PGMs have been used for the quantification of extra-terrestrial components and the identification of impactor types in impact deposits by using concentrations and inter-element ratios of PGMs (Koeberl et al., 2012). PGE anomalies can also be used to distinguish between terrestrial and cosmic origin (e.g., Koeberl, 2014). However, there have been no published studies of specific Pt stable isotope variations in natural terrestrial samples (Creech et al., 2014). Thus, PGEs may present a possible context for stable isotope fingerprinting of platinum source materials.

The aim of this investigation is a pilot study to investigate whether platinum isotopes can be a used as a fingerprinting method to determine the geographical origin, and furthermore, to possible determine whether platinum from smartphones derived from new metal material or from recycled metal material (due to the fact that platinum has a high recycling rate). A requirement for the accurate assignment of the provenance is the determination of the isotopic composition in raw primary samples from ores of the main provinces. Many of the PGM-provinces are distinct from other metal deposits in that most of the large PGM-structures have formed in extraordinary occasions. For example, the Bushveld complex is the world's largest layered intrusion (South African Mineral Council, 2020), and the large amount of PGE in the Sudbury structure is likely due to melting of the entire crust during an impact event (after Huber et al., 2014).

Investigation of the isotopic composition from primary samples needs to disclose first if there is a distinction between platinum provinces. It then needs to be decided whether it is feasible to further investigate samples with high platinum content from smartphones and, for comparison, of a platinum sample from a recycling facility for isotopic composition. Thus, after platinum isotope separation, it needs to be investigated whether an isotopic signature for each location is possible, before a comparison of primary platinum signatures to platinum signatures from smartphones and recycling can be facilitated. The literature for platinum research is extensive (e.g., Gros et al., 2002; Tredoux et al., 2009; Creech et al., 2013; Oberthür, 2016), yet a detailed isotopic analysis has not been completed (Creech et al., 2014). Initial work very valuable for the topic has been accomplished by Creech et al. (2014). This chapter

4.4.1. Samples

Samples were selected by current main mining localities, and a number of museums, companies, and research facilities were contacted for provision of samples. Also, samples from smartphones with a high platinum content (the contacts for the SIM-card) were selected for comparison and further examination.

For the geological sections, 18 samples were collected to comprise a representative overview, based on availability and geographical origin, of main platinum provinces as well as including smaller provinces:

- **Bushveld complex** (South Africa): large layered igneous intrusion (Bushveld Magmatic Province), age around 2.1 Ga, size ca. 450 km x 350 km; consisting of 3 reefs (called horizons) (Buchanan et al. 1999; Nomade et al., 2004)

  -> 9 rock samples, 3 from each reef: Merensky, UG2 (Upper Group 2) Chromitite, Platreef
- **Great Dyke** (Zimbabwe): Layered ultramafic intrusion, age around 2.5 Ga, size ca. 4-10 km x 550 km (Wilson and Pendergast, 2011; Oberthuer, 2016)

  -> 2 rock samples
- **Noril'sk** (Siberia, Russia): development connected to Siberian trap basalts, age around 249 Ma; largest Ni-Co-Pd deposit in the world (Naldrett 1997; Yakubchuk & Nikishin, 2004)

  -> 1 processed sample (concentrate powder provided from company Noril'sk Nickel with 25 % Pt-content)
- **Lac de Illes** (Ontario, Canada): layered gabbroic intrusion, age around 2.7 Ga, size 30 x 2 km (Sutcliff et al., 2011)

  -> 2 rock samples (sulfide rich pods)
- **Sudbury** (Ontario, Canada): large Impact-Structure, age 1.86 Ga; Sudbury Igneous complex size ca. 30 x 18 km (after Koeberl et al., 2012; Huber et al., 2014)

  -> 2 rock samples
- **Stillwater** (Montana, USA): layered mafic intrusion, age around 2.7 GA, size: 1.6 x 45 km; small desposit but has the highest PGM-grade worldwide (Stillwater Mining, 2020)

  -> 1 processed sample (concentrate powder provided from Stillwater Mining Inc.)

One of the most widespread Pt-mineral is sperrylite [$PtAs_2$] which occurs in most PGM-deposits (Oberthuer, 2016). However, processed samples were a variety of rock types where no distinct mineral forms were visible to the naked eye. For digestion, some samples needed to be processed with a geological hammer (by Eastwing, USA).

Rock samples were first processed using the same digestion method for smartphone samples. Pt isotopes were then measured with a Multi Collector ICP Mass Spectrometer (MC-ICP-MS) by Nu Instruments (NuPlasma II) at Helmholtz-Centrum Geesthacht, Centre for Materials and Coastal Research. However, elemental matrix interferences revealed that further separation of platinum from other PGEs iridium, palladium, osmium, rhenium, and ruthenium was needed for further platinum isotope investigation. An initial separation was then facilitated with anion exchange separation columns following Pt-separation protocol from Chu et al. (2014). However, this was not sufficient for a detailed analysis.

4.4.2. Outlook

Preliminary results of the described platinum samples show a potential for different isotopic compositions of samples. However, preliminary measurements of digested samples revealed that a complete separation of PGMs and a separate digestion protocol needs to be set up for detailed isotope investigation of platinum. Setup of a complete separation to eliminate elemental matrix interferences would go beyond the scope of this thesis. Thus, preliminary data will not be further discussed here and investigations then focused on other raw material topics, see **chapter 5**.

4.5. References

Al Barazi S (2018). Rohstoffrisikobewertung – Kobalt. DERA Rohstoffinformationen 36: 120 S.; Berlin. 978-3-943566-48-2. Access at https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-36.pdf? accessed Aug 2020

Amnesty International (2016). Democratic Republic of Congo: "This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt. Report. https://www.amnesty.org/en/documents/afr62/3183/2016/en/ accessed Aug 2020

Argus Metals (2019): Argus White paper: electronic metals demand. Spotlight on 5G technologies. https://www.argusmedia.com/-/media/Files/white-papers/electronic-metals-demand-spotlight-on-5g-technologies accessed Aug 2020

Bauer D, Diamond D, Li, Sandalow D, Telleen P, and Wanner B (2011). U.S. Department of Energy Critical Materials Strategy. https://doi.org/10.2172/1000846

BGR (20120). CTC – Certified Trading Chains. https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/CTC/Concept_MC/CTC-Standards-Principles/ctc_standards-principles_node_en.html accessed July 2020

Buchholz, Head of German Mineral Resources Agency at BGR, personal statement, July 2020.

Chancerel P, Rotter VS, Ueberschaar M, Marwede M, Nissen NF, Lang K (2013). Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment. Waste. Manag. Res. 31. https://doi.org/10.1177/0734242X13499814

Chu Z, Yan Y, Chen Z, Guo J, Yang Y, Li C, Zhang Y (2014). A Comprehensive Method for Precise Determination of Re, Os, Ir, Ru, Pt, Pd Concentrations and Os Isotopic Compositions in Geological Samples. Geostandards and Geoanalytical Research 39(2) doi: www.10.1111/j.1751-908X.2014.00283.x

Cobelo-García A, Filella M, Croot P. Frazzoli C Du Laing G, Ospina-AlvarezN, Rauch S, Salaun P, Schäfer J, Zimmermann S (2015). COSTaction TD1407: network on technology-critical elements (NOTICE)—from environmental processes to human health threats. Environ. Sci. Pollut. Res. 22. https://doi.org/10.1007/s11356-015-5221-0

Cox DP and Singer DA (2011). Mineral Deposit Models. USGS Publication. https://pubs.usgs.gov/bul/b1693/html/bull1nzi.htm accessed Aug 2020

Creech JB, Baker JA, Handler MR, Schiller M, Pizzarro M (2013). Platinum stable isotope ratio measurements by double-spike multiple collector ICPMS. Journal Analytical Atomic Spectrometry.28:853–865. http://dx.doi.org/10.1039/C3JA50022E.

Creech JB, Baker JA, Handler MR, Pizarro M (2014). Platinum stable isotope analysis of geological standard reference materials by double-spike MC-ICPMS. Chemical Geology, 363: 293-300 https://doi.org/10.1016/j.chemgeo.2013.11.009

DERA (2019). DERA Rohstoffliste 2019. DERA Rohstoffinformationen 40. Berlin ISBN: 978-3-943566-87-1 Access at https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-40.pdf? accessed July 2020

Dold B (2009). Sustainability in metal mining: from exploration, over processing to mine waste management. Reviews in Environmental Science and Bio/Technology. 7, 275. www.doi.org/10.1007/s11157-008-9142-y

Ellen McArthur Foundation (2013). Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf accessed July 2020

Erdmann L and Graedel, TE (2011). Criticality of non-fuel minerals: a review of major approaches and analyses. Environ. Sci. Technol. 45. https://doi.org/10.1021/es200563g

EITI Extractive Industries Transparency Initiative (2020). Natural resources. https://eiti.org/natural-resources accessed Aug 2020.

European Commission (2012). Life cycle indicators for waste management: development of life cycle based macro-level monitoring indicators for resources, products and waste for the EU-27. European Commission, Joint Research Centre, Institute for Environment and Sustainability. 90 pages. Ispra, Italy.

EU commission (2014). Frequently Asked Questions: Responsible sourcing of minerals originating conflict-affected and high-risk areas: towards an integrated EU approach.

https://ec.europa.eu/commission/presscorner/detail/lv/MEMO_14_157 accessed Aug 2020

EU Commission (2020a). A new Circular Economy Action Plan For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, The European Economic and social committee and the committee of the regions. https://ec.europa.eu/info/sites/info/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf accessed Aug 2020

EU Commission (2020b). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability https://ec.europa.eu/docsroom/documents/42849 accessed Sep, 2020

EU Parliament (2017). Press release. Conflict minerals: MEPs secure due diligence obligations for importers https://www.europarl.europa.eu/news/en/press-room/20170308IPR65672/conflict-minerals-meps-secure-due-diligence-obligations-for-importers accessed Aug 2020

EUROSTAT (2020). Resource productivity statistics. Statistics Explained. Download at https://ec.europa.eu/eurostat/statistics-explained/pdfscache/30598.pdf accessed Aug 2020

Fizaine F (2013). Byproduct production of minor metals: Threat or opportunity for the development of clean technologies? The PV sector as an illustration. Res. Pol. 38 (3). https://doi.org/10.1016/j.resourpol.2013.05.002

Forti V, Baldé CP, Kuehr R, Bel G (2020). Global E-Waste monitor. Quantities, flows, and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam. 120 pages. Available at http://ewastemonitor.info/wp-content/uploads/2020/07/GEM_2020_def_july1_low.pdf# accessed Aug 2020

Frenzel M, Mikolajczak C, Reuter M, Gutzmer J (2015). Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium. Res. Pol. 52. https://doi.org/10.1016/j.resourpol.2017.04.008

Friege H (2012). Review of material recovery from used electric and electronic equipment: alternative options for resource conservation. Waste Management and Research. 30 (9). https://doi.org/10.1177/0734242X12448521

Gaustard G, Krystofik M, Bustamante M, Badami B (2018). Circular economy strategies for mitigating critical material supply issues. Resources Conservation Recycling. 135. https://doi.org/10.1016/j.resconrec.2017.08.002

Giljum S, Bruckner M and Martinez A (2014). Material Footprint Assessment in a Global Input-Output Framework. Journal of Industrial Ecology, 19 (5).pp. 792-804. https://doi.org/10.1111/jiec.12214

Graedel TE, Harper EM, Nassar NT, Reck BK (2013). On the materials basis of modern society, PNAS 112. 6295–6300, http://dx.doi.org/10.1073/pnas.1312752110

Graedel TE, Allwood J, Birat JP, Reck BK, Sibley SF, Sonnemann G, Buchert M, Hagelüken C (2011). Recycling Rates of Metals – A Status Report.. ISBN 978-92-807-3161-3. https://www.resourcepanel.org/reports/metal-recycling (accessed June, 2020)

Gros M, Lorand J, Luguet A (2002). Analysis of platinum group elements and gold in geological materials using NiS fire assay and Te coprecipitation; the NiS dissolution step revisited. Chemical Geology. 185:179–190.

Gunn G (2014). (Ed).Critical Metals Handbook. John Wiley & Sons, Oxford. https://doi.org/10.1002/9781118755341.ch12

Hagelüken, C & Corti, CW (2010). Recycling of gold from electronics: Cost-effective use through 'Design for Recycling'. Gold. Bull. 43: 209. https://doi.org/10.1007/BF03214988

Hagelüken C, Meskers C (2010). Complex life cycles of precious and special metals. In: Graedel T, van der Voet E (Eds.) Linkages of Sustainability. MIT Press. ISBN: 0-262-01358-4. pp. 163-197

Hagelüken C (2014). Recycling of (critical) metals. Chapter 3 in Gunn G (Eds) Critical Metals Handbook. John Wiley & Sons, Oxford. https://doi.org/10.1002/9781118755341.ch3

Hardman S & Steinberger-Wilckens R (2014). Mobile phone infrastructure development: Lessons for the development of a hydrogen infrastructure. International Journal of Hydrogen Energy. 39 (16) pp 8185-8193. https://doi.org/10.1016/j.ijhydene.2014.03.156

Holgersson BS, Teenari M, Bjoerkman C and Cullbrand K (2018). Analysis of the metal content of small-size waste electric and electronic equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resour. Conserv. Recycl. 133. https://doi.org/10.1016/j.resconrec.2017.02.011

Huber M, McDonald I, and Koeberl C (2014). Petrography and geochemistry of ejecta from the Sudbury impact event. Meteoritics and Planetary Science 49, 1749–1768. https://doi.org/10.1111/maps.12352

Huisman J, Leroy P, Tertre F, Söderman M, Chancerel P, Cassard D, Løvik A, Wäger P, Kushnir D, Rotter VS, Mählitz P, Herreras L, Emmerich J, Hallberg A, Habib H, Wagner M, Downes S (2017). Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report. http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf accessed July 2020

IPIS International Peace Information Service (2002). Supporting the War Economy in the DRC: European Companies and the Coltan Trade. https://ipisresearch.be/publication/supporting-the-war-economy-in-the-drc-european-companies-and-the-coltan-trade/ accessed Aug 2020

ITU International Telecommunication Union (2016). ICT Facts and Figures 2016. http://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx accessed Aug 2020

ITU International Telecommunication Union (2020). Mobile infrastructure sharing. Website. https://www.itu.int/itunews/manager/display.asp?lang=en&year=2008&issue=02&ipage=sharingInfrastructure-mobile accessed Aug 2020

ITU International Telecommunication Union (2019): The ICT Development Index (IDI). Methodology, indicators and definitions. https://www.itu.int/en/ITU-D/Statistics/Documents/statistics/ITU_ICT%20Development%20Index.pdf

Izatt RM (2016). Metal Sustainability: Global Challenges, Consequences, and Prospects. Wiley and Sons. 552 pages. ISBN: 978-1-119-00910-8

Jowitt SM, Werner TT, Weng Z, Mudd G (2017). Recycling of the rare earth elements. Current Opinion in Green and Sustainable Chemistry https://doi.org/10.1016/j.cogsc.2018.02.008

Junge M, Oberthür T, Kraemer D, Melcher T, Strauss H (2018). Distribution of platinum-group elements in pristine and near-surface oxidized Platreef ore and the variation along strike, northern Bushveld Complex, South Africa. Mineralium Deposita. https://doi.org/10.1007/s00126-018-0848-7

Koeberl C (2014). The Geochemistry and Cosmochemistry of impacts. In: Holland HD and Turekian KK (Eds). Treatise on geochemistry. 2nd Edition, vol. 2 (Planets asteroids, comets and the solar system, pp73-118. Oxford. Elsevier.

Koeberl C, Claeys P, Hecht L, McDonald (2012). Geochemistry of Impactites. Elements. 8(1):37–42. www.doi.org/10.2113/gselements.8.1.37

Liedtke M and Huy D (2018). Rohstoffrisikobewertung – Gallium. DERA Rohstoffinformationen 35: 86 S.; Berlin. ISBN: 978-3-943566-50-5. https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_gallium-2018.pdf? accessed July 2020

Lovik A, Hagelüken C, Wäger P(2018). Improving supply security of critical metals: Current developments and research in the EU. Sustainable Materials and Technologies 15. https://ww.doi.org/10.1016/j.susmat.2018.01.003

Mathieux F, Ardente F, Bobba S, Nuss P, Blengini G, Alves Dias P, Blagoeva D, Torres De Matos C, Wittmer D, Pavel C, Hamor T, Saveyn H, Gawlik B, Orveillon G, Huygens D, Garbarino E, Tzimas E, Bouraoui F and Solar S (2017). Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, https://doi.org/10.2760/378123

Melcher F, Sitnikova MA, Graupner T, Martin N, Oberthür T, Henjes-Kunst F, Gäbler E, Gerdes A, Brätz H, Davis DW (2008). Fingerprinting of conflict minerals: Columbite-tantalite ("coltan") ores. SGA News,23, 7–14.

Mudd G; Weng Z; Jowitt S A (2013). Detailed Assessment of Global Cu Resource Trends and Endowments. Econ. Geol. 2013, 108, 1163–1183. https://doi.org/10.2113/econgeo.108.5.1163

Naldrett AJ (1997). Key factors in the genesis of Noril'sk, Sudbury, Jinchuan, Voisey's bay and other world-class Ni-Cu-PGE deposits: implications for exploration. Australian Journal of Earth Sciences, 44 (3), pp. 283-315.

Nassar NT, Graedel, TE, Harper EM (2015). By-product metals are technologically essential but have problematic supply. Sci. Adv. 1. https://dx.doi.org/10.1126%2Fsciadv.1400180

NSTC (2016). National Science Technology Council. CSMSC Assessment of Critical Minerals Report. https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf (accessed June 2020)

Nelen D, Manshoven S, Peeters JR, Vanegas P, Hase N, Vrancken K, (2014). A multidimensional indicator set to assess the benefits of WEEE material recycling. Jour. of Clean. Prod. Vol 83. https://doi.org/10.1016/j.jclepro.2014.06.094

Nomade S, Renne P, Merkle R (2004). 40Ar/39Ar age constraints on ore deposition and cooling of the Bushveld Complex, South Africa. Journal of the Geological Society 161(3):411-420. https://doi.org/10.1144/0016764903-065

Oberthuer T (2016). The mineralogical siting/deportment of platinum-group elements in Ni-Cu-PGE ores. (1) The most important PGM, and (2) PGE in sulfides. https://doi.org/10.13140/RG.2.2.15874.07365

OECD (2010a). A Sustainable Materials Management Case Study: critical metals and mobile devices. Report to the commission from the Working Group on Waste Prevention and Recycling. Download at https://www.oecd.org/env/waste/asustainablematerialsmanagementcasestudycriticalmetalsandmobiledevices.htm accessed July 2020

OECD (2010b). Due diligence guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. Paris: Organisation for Economic Cooperation and Development. https://www.oecd.org/corporate/mne/mining.htm accessed Aug 2020

OECD Organization for Economic Co-operation and Development (2011). Towards Green Growth: Monitoring Progress (OECD Indicators). Paris. 114 pages. Available at https://www.oecd.org/greengrowth/48224574.pdf accessed July 2020

OECD (2019). Global Material Resources Outlook to 2060 – Economic drivers and environmental consequences, OECD Publishing, Paris. https://doi.org/10.1787/9789264307452-en.

Pohl WL (2011). Economic Geology, Principles and Practice: Metals, Minerals, Coal and Hydrocarbons— an Introduction to Formation and Sustainable Exploitation of Mineral Deposits. 678 Pages. Wiley Blackwell. ISBN: 978-1-444-33663-4

Pearce DW and Turner RK (1990). Economics of Natural Resources and the Environment. Harvester Wheats, Brighton. 392 pages.

Poulsen F (2010). Blood in the Mobile.The dark side of our cell phones. Movie Documentary, 83 min. Spacesheep Movies. https://www.imdb.com/title/tt1763194/ accessed July 2020

PWC (2018). Mine 2018. Outlook. https://www.pwc.com/gx/en/mining/assets/pwc-mine-report-2018.pdf accessed July 2020

Reck B and Graedel TE (2012). Challenges in Metal Recycling. Science. 337 (6095) 695. https://doi.org/10.1126/science.1217501

Redlinger M, Eggert R, Woodhouse M (2015). Evaluating the availability of gallium, indium and tellurium from recycled photovoltaic modules. Sol. Energy Mater. Sol. Cells. 138. https://doi.org/10.1016/j.solmat.2015.02.027

Reimer M, Schenk-Mathes H, Hoffman M and Elwert T (2018). Recycling Decisions in 2020, 2030, and 2040—When Can Substantial NdFeB Extraction be Expected in the EU? Metals. 8(11). https://doi.org/10.3390/met8110867

Reuter M and van Schaik A (2012). Opportunities and limits of recycling: A dynamic-model-based analysis. MRS Bulletin. 37 (4): 339-347 https://doi.org/10.1557/mrs.2012.57

Ritchie, Roser, Mispy, Ortiz-Ospina (2018). Measuring progress towards the Sustainable Development Goals. Website www.SDG-Tracker.org accessed Aug 2020

RMI Responsible Minerals Initiative (2020). Minerals Due Diligence. http://www.responsiblemineralsinitiative.org/minerals-due-diligence/ accessed Aug 2020

RSN Responsible Sourcing Network (2020). Minerals. https://www.sourcingnetwork.org/minerals accessed Aug 2020

RSBN Responsible Sourcing Blockchain Network (2020). https://www.rcsglobal.com/blockchain-traceability/ accessed Aug 2020

Reuter M and van Schaik A (2012). Opportunities and limits of recycling: A dynamic-model-based analysis. MRS Bulletin. 37 (4): 339-347 https://doi.org/10.1557/mrs.2012.57

Reuter M A, Hudson C, van Schaik A, Heiskanen K, Meskers C, Hagelüken C (2013). Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the Inter-national Resource Panel. ISBN: 978-92-807-3267-2. https://www.resourcepanel.org/reports/metal-recycling accessed July 2020

Reuter M, van Schaik A, Gutzmer J, Bartie N, Abadias-Llamas A (2019). Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annual Review of Material Research. 49:253-274. https://doi.org/10.1146/annurev-matsci-070218-010057

Rötzer, N., Schmidt, M. (2020). Historical, Current, and Future Energy Demand from Global Copper Production and Its Impact on Climate Change. Resources 2020, 9, 44. https://www.doi.org/10.3390/resources9040044

Sarath P, Bonda S, Mohanty S, and Navak S (2015). Mobile phone waste management and recycling: Views and trends. Waste Management. 46. pp. 536-545. https://doi.org/10.1016/j.wasman.2015.09.013

Schrijvers D, Hool A, Blenginid GA, Chene WQ, Dewulf J, Eggert R, Ellen L, Gauss R, Goddin J, Habib K, Hagelüken C, Hirohatam A, Hofmann-Amtenbrink M, Kosmol J, Le Gleuherp M, Grohol M, Kur A, Lees MH, Liu G, Nansai K, Nuss P, Peck D, Reller A, Sonnemann G, Tercero L, Thorenz A, Wäger PA (2020). A review of methods and data to determine raw material criticality. Resources Conservation and Recycling. 155. 104617. https://doi.org/10.1016/j.resconrec.2019.104617

Schulz KJ, Piatak NM, and Papp JF (2017a). Niobium and Tantalum. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the United States - Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802M.

Stillwater Mining. Company Webseite. http://www.stillwatermining.com accessed Aug 2020

Stahel W and Reday G (1976). Jobs for tomorrow: the potential for substituting manpower for energy. 116 pages. Vantage Press California. ISBN 9780533047994

Tanskanen P (2013). Management and recycling of electronic waste. Acta Materialia. 61 (3). https://doi.org/10.1016/j.actamat.2012.11.005

Teehan P & Kandlikar M (2014). Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products (2013). Environmental Science & Technology. 47(9):3997–4003 https://doi.org/10.1021/es303012r

Tukker A, Bulavskaya T, Giljum S, de Koning A, Lutter S, Simas M, Stadler K, Wood R (2014). The Global Resource Footprint of Nations. Carbon, water, land and materials embodied in trade and final consumption. Leiden/Delft/Vienna/Trondheim.39 pages. Available at https://www.exiobase.eu/index.php/publications/creea-booklet/ accessed Aug 2020

UN United Nations (2001). Press Release. Security Council condems illegal exploitation of Democratic Republic of Congo's natural resources https://www.un.org/press/en/2001/sc7057.doc.htm accessed Aug 2020

UN United Nations (2015). Sustainable Development goals. https://sdgs.un.org/goals accessed Aug 2020

UNEP United Nations Environmental Program (2011). Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel. Fischer-Kowalski M, Swillin, M, von Weizsäcke, EU, Ren Y, Moriguch Y, Cran W, Krausman F, Eisenmenge N, Giljum S, Hennicke P, Romero Lankao P, Siriban Manalang A, Sewerin S. Available at http://wedocs.unep.org/handle/20.500.11822/9816 accessed Aug 2020

USGS United States Geological Survey (2017). Critical Minerals of the United States. https://www.usgs.gov/news/critical-minerals-united-states accessed July 2020

van Schaik A & Reuter M (2014). Material-Centric (Aluminum and Copper) and Product-Centric (Cars, WEEE, TV, Lamps, Batteries, Catalysts) Recycling and DfR Rules. In: Worrell, Reuter (Ed.) Handbook of Recycling. ElSevier. Pages 307-378 https://doi.org/10.1016/B978-0-12-396459-5.00022-2

Wiedmann TO, Schandl H, Lenzen M, Moran D, Suh S, West J, and Kanemoto K (2013). The material footprint of nations.: PNAS 112 (20); 6271-6276. https://doi.org/10.1073/pnas.1220362110

5. Metallic resources in smartphones

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Published 2020 in **Resources Policy, Vol 68.**
www.doi.org/10.1016/j.resourpol.2020.101750

Submitted 12 Feb 2020, accepted 04 June 2020.

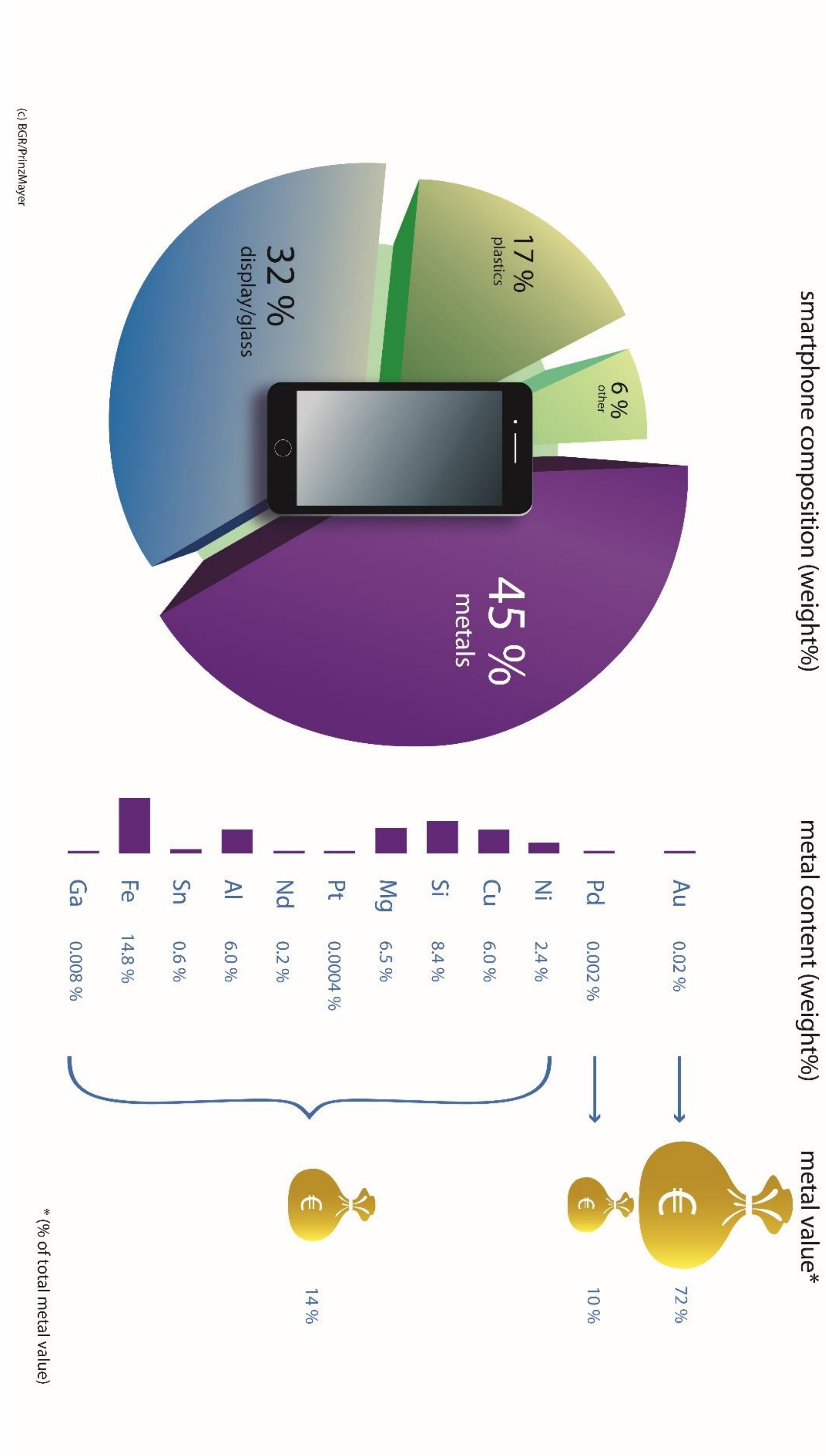
Abstract

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 2012-2017 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 2012-2017 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.

Keywords

smartphones; recycling; technology metals; ore grades; WEEE; metal prices

Graphical abstract



5.1. 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 at 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., Graedel et al., 2013; Reuter 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., Mathieu et al., 2018), "technology metal" (e.g., UNEP, 2013), and "technology critical element" (Cobelo-Garcia 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 (Mathieu et al., 2018). 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; Mathieu et al., 2018). In this paper, the focus is set on metallic elements 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; UNEP, 2011, 2013; 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, 2019; 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.

5.1.1. Why smartphones?

By number, a large proportion of (W)EEE is consumer electronics, such as Information and Communication Technology (ICT) devices (EU, 2011). Particular interest lies in mobile phones, as they are often cited as containing many of the "technology" metals (Hagelüken and Meskers, 2010; UNEP 2012), and mobile phones have been the subject of continuous collection and recycling studies (e.g. UNEP, 2010; Polak et al., 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 2012-2017 (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 2012-2017 (Statista, 2019b). Yet, mobile phones in general only have a low global return rate of 5-10 % (UNEP, 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., 2017. 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 UNEP (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).

5.1.2. 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 (Überschaar, 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 Schnaik, 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.

5.2. Materials and methods

5.2.1. 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.

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 mineral commodity information (United States Geological Survey). 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.

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 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 (Wellmer et al., 1990; 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.

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 (UNEP, 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 PCB 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.

5.3. Results

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 (**Figure 5.1**), averaged total content in the three smartphones is low (each group in descending content weight order):

- 7 metals encompass more than 1 g on average per single device: Fe, Si, Mg, Al, Cu, Ni, Cr
- 8 metals are contained with more than 0.1 g (0.1 g < x < 1 g): Sn, Zn, Sr, Ba, W, Nd, Mn, Ti.
- 9 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 **Figure 5.2**. 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.

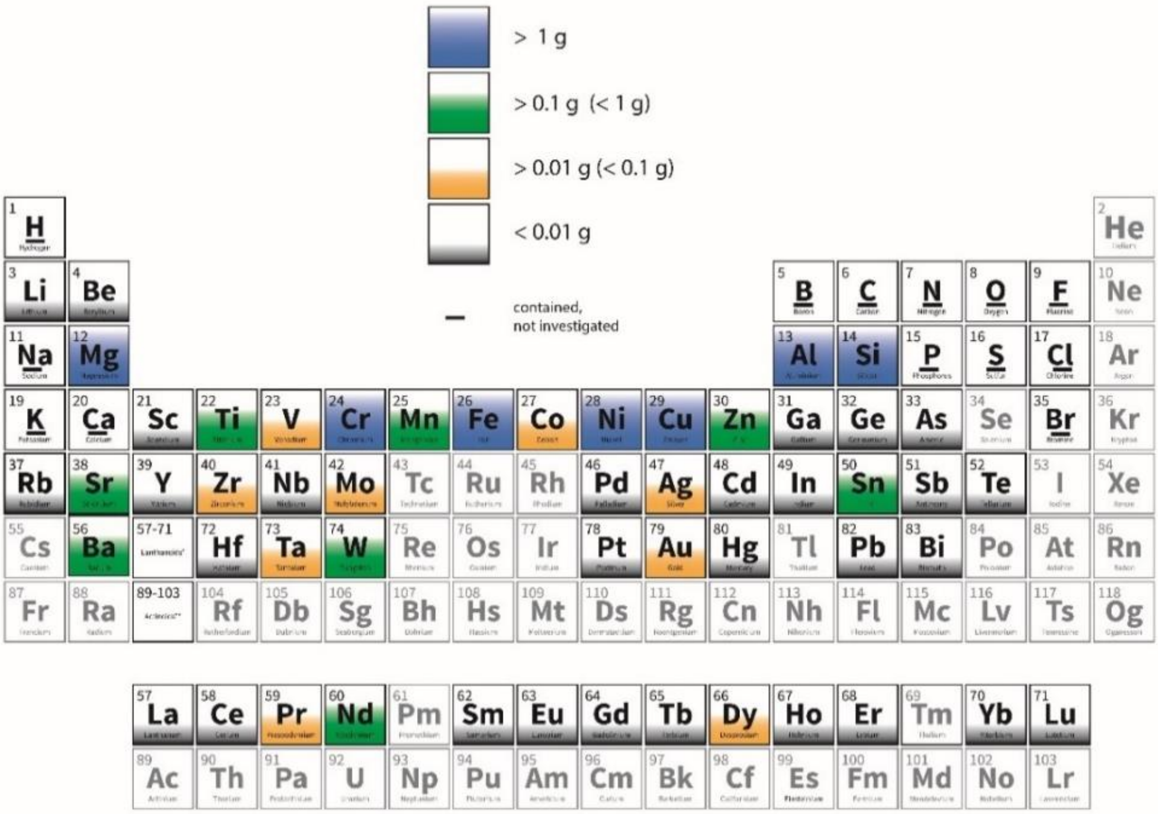


***Figure 5.1**: Investigated elements in selected smartphones and their average content.*

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.

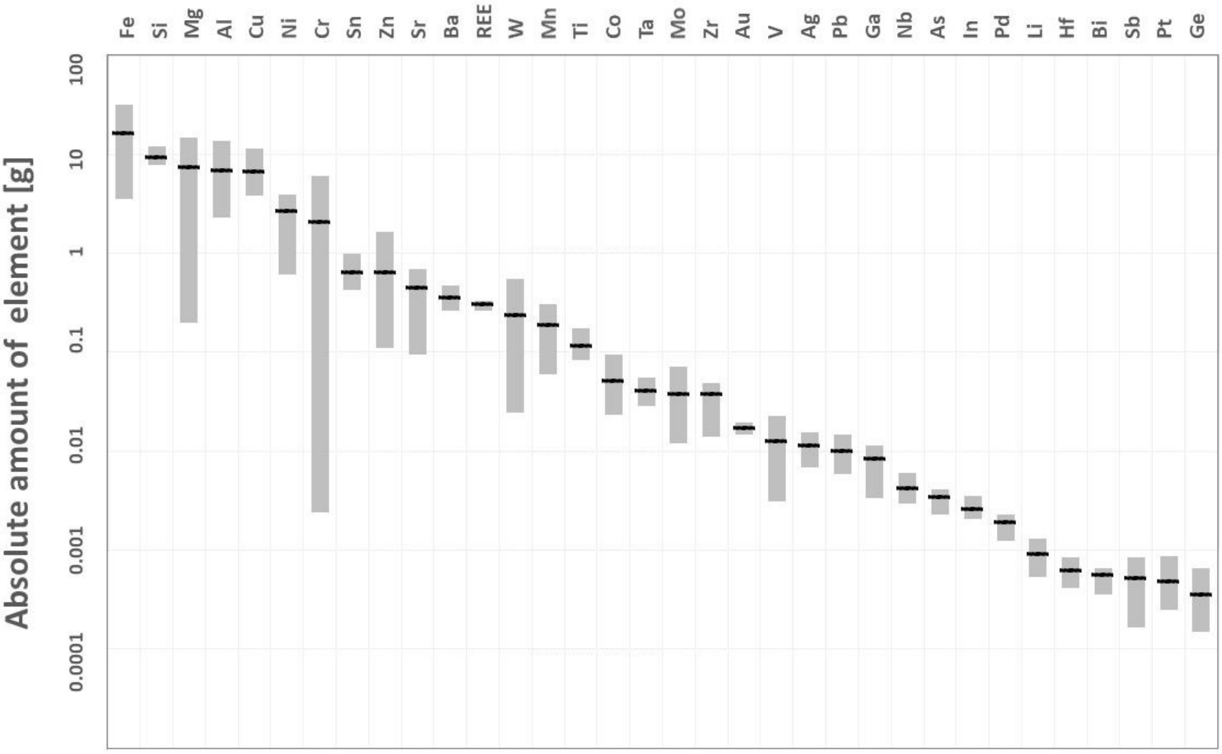


Figure 5.2: Total measured metal content in smartphones in descending order. Black lines are mean measurements; grey shaded areas show the content range from the three investigated smartphones (minimum and maximum values). Rare Earths elements (Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu, Y) are combined and are shown here as REE. Note the logarithmic X scale.

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 5.1**.

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	663,000,000
Ni	19,000	304,000,000
Cu	49,000	280,000,000
Si	69,000	224,000,000
Mg	54,000	126,000,000
Pt	4	98,000,000
Nd	42	89,000,000
Al	49,600	86,000,000
Sn	5,000	79,000,000
Fe	121,000	64,000,000

***Table 5.1**: 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.*

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 (UNEP, 2011), and as they gain the most value. Yet, different recycling facilities use different technologies. **Figure 5.3** 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 these four metals (in the set timeframe ranging from 82-90 %, with a value of 0.58 to 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

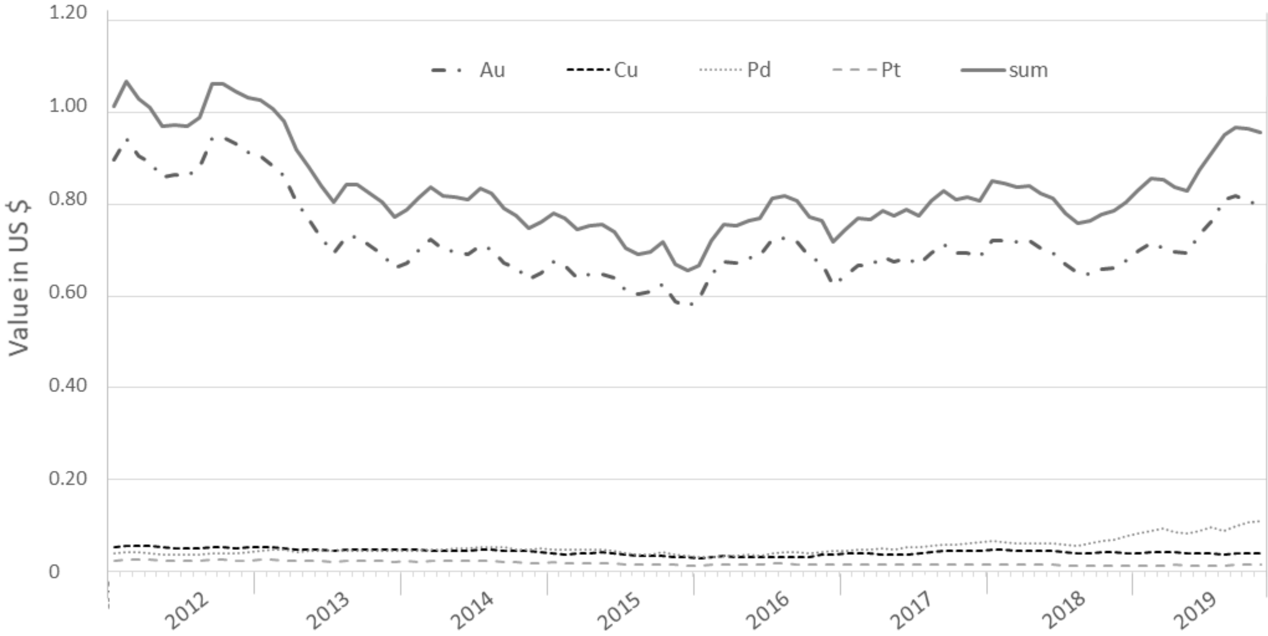


Figure 5.3: The value of Au, Pd, Pt, and Cu based on their fractional content in smartphones, calculated over the timeframe 2012-2019. The top line represents the sum of their fractional values.

magnets) as well as their fractional pure metal value is given in **Table 5.2**. 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.

	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	} 0.95 US $
			Cu 6606.41	
			Pd 1.91	
			Pt 0.48	
			REE 303.39	0.02 US $
pcb	15.7262	0.93	Au 15.13	} 0.86 US $
			Cu 6504.64	
			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 $

__Table 5.2__: location, weight and metal content of smartphone components for value comparison; Nov 2019 prices.

Selected metals: geological occurrence and comparison of 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 5.3** (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.

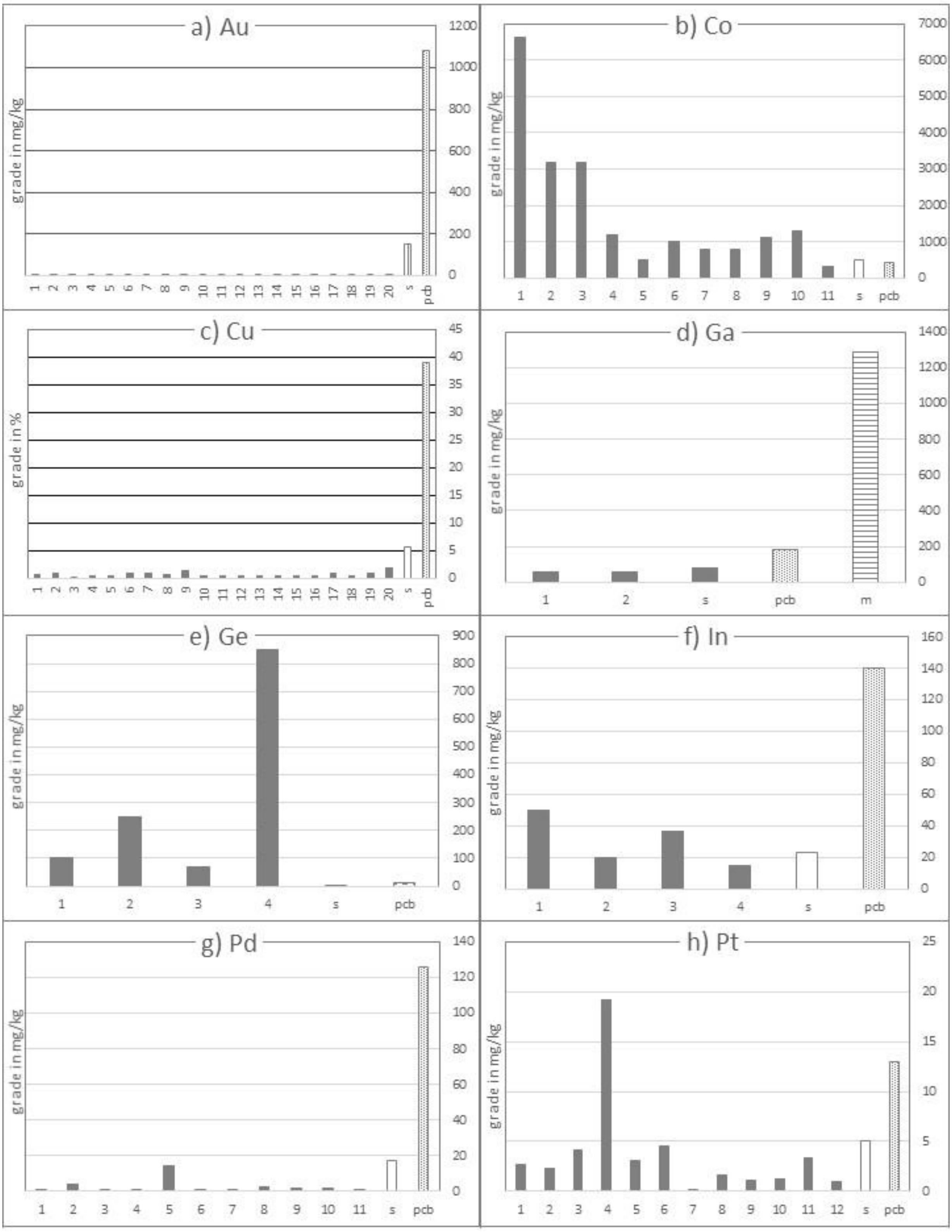
Rare earth element mining data are only available as Rare Earth Oxides (REO); thus, shares are only estimated due to conversion from REE to REO. Mining data for REO is without estimated illegal production.

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 **Figure 5.4**.

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**.

***Table 5.3**: 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 2012-2017 (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	3,222 (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	3,400 – 20,000 (aver 4,900)	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)	2,251 (REE)	Approx. 1.77	Approx. 6 days
Tantalum (Ta)	0.7 -2	182-250 (1)	362	*DR Congo 41, Rwanda 19, Brazil 14	*1,491 (1)	298	20.01	73 days


a) Au
grade in mg/kg
b) Co
grade in mg/kg
c) Cu
grade in %
d) Ga
grade in mg/kg
e) Ge
grade in mg/kg
f) In
grade in mg/kg
g) Pd
grade in mg/kg
h) Pt
grade in mg/kg

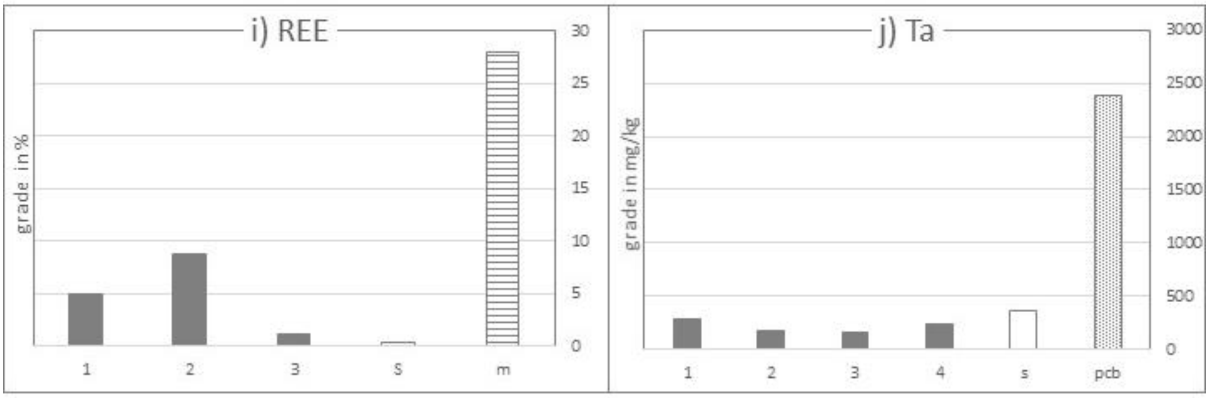


__Figure 5.4__: Plots of metal content of currently (2016 data) mined primary ores in comparison to measured metal content in smartphones for __a) Gold__ (20 largest mine sites, covering ~20 % of global Au-production), __b) Cobalt__ (covering 74 % of LSM), __c) Copper__ (20 largest mine sites, covering 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.

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 & Huy, 2018; Frenzel et al., 2015); Ge (Frenzel et al., 2015); In (Loganc et al., 2015); REE (Van Gosen et al., 2017; Zhou et al., 2017); Ta (Damm, 2019; Schulz et al., 2017a).

Pd, Pt: Mine sites no 1 (Pd) and no 12 (Pt) have low grades at ~ 0.3 mg/kg that are almost not visible in this figure.

5.4. 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., (2017). 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 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 Schnaik, 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, 2012). 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 (UNEP, 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 at 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 7,890 and Ta of 2,365 with few companies in few countries dominating production (DERA, 2019).

The display of technical devices is often termed as the In carrier in smartphones (e.g., Buchert et al., 2014). 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 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 PCB is below the Co content in currently mined ores, and due to the complex built of PCB 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,

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	-

Table 5.4: 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.

2019), 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 5.4**), and permanent magnets have already been termed as the most valuable waste streams for REE (e.g., Jowitt et al.,

2018). Yet, REE recycling regarding magnets mainly focuses on recovery from permanent magnet production processes and reasons for this have been summarized by Reimer at 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 PCB (see **Table 5.4**), 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 & 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; Husimann 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, 2020or 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 Schnaik, 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.

Thermodynamics are another key factor in regards to the circular economy concept (see UNEP, 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 (UNEP, 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 & van Schaik, 2012; Hagelüken 2014; Überschaar 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 (Überschaar, et al., 2018). To recover more Ta from consumer products, additional presorting and separation paths of the electronics would be necessary (Graedel, 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.

5.5. 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).

5.6. 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.

5.7. References

1. Al Barazi S (2018). Rohstoffrisikobewertung – Kobalt. DERA Rohstoffinformationen 36: 120 S.; Berlin. 978-3-943566-48-2. Access at https://www.deutsche-

rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-36.pdf? (accessed June 2020)

2. Ansorge L, CEO of Rockling and Magcycle. private communication January 2020.
3. Bauer D, Diamond D, Li, Sandalow D, Telleen P, and Wanner B (2011). U.S. Department of Energy Critical Materials Strategy. https://doi.org/10.2172/1000846
4. BGS British Geological Survey (2011). Rare Earth Elements - Mineral Profile. Access at https://www.bgs.ac.uk/mineralsuk/statistics/mineralProfiles.html (accessed June 2020)
5. Blengini GA, Nuss P, Dewulf J, Nita V, Peiro LT, Vidal-Legaz B, Latunuss C, Mancini L, Blagoeva D, Pennington D, Pellegrini M, van Maercke A, Solar S, Grohol M, Ciupagea C (2017). EU methodology for critical raw materials assessment. Policy needs and proposed solutions for incremental improvements. Res Pol. 53. https://doi.org/10.1016/j.resourpol.2017.05.008
6. Bookhagen B, Obermaier W, Opper C, Koeberl C, Hofmann T, Prohaska T, Irrgeher J (2018). Development of a versatile analytical protocol for the comprehensive determination of the elemental composition of smartphone compartments on the example of printed circuit boards. Anal Meth. 10 https://doi.org/10.1039/C8AY01192C
7. Bookhagen B, Nordmann J, Dyrnes I, Stengel O, Schmidt N-H (2013). Acceptance of Mobile Phone Return Programs: A Case Study Based Analysis. - In: Hilty, LM, Aebischer B, Andersson G, Lohmann W (Eds.), - Proceedings, International Conference on Information Communication Technologies for Sustainability. Zurich. p. 59-64.
8. Chancerel P, Rotter VS, Ueberschaar M, Marwede M, Nissen NF, Lang K (2013). Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment. Waste. Manag. Res. 31. https://doi.org/10.1177/0734242X13499814
9. Cobelo-García A, Filella M, Croot P. Frazzoli C Du Laing G, Ospina-AlvarezN, Rauch S, Salaun P, Schäfer J, Zimmermann S (2015). COSTaction TD1407: network on technology-critical elements (NOTICE)—from environmental processes to human health threats. Environ. Sci. Pollut. Res. 22. https://doi.org/10.1007/s11356-015-5221-0
10. Cox DP and Singer DA (2011). Mineral Deposit Models. USGS Publication. https://pubs.usgs.gov/bul/b1693/html/bull1nzi.htm (accessed June 2020)
11. Damm S (2018). Rohstoffrisikobewertung – Tantal – DERA Rohstoffinformationen 31: 82 S.; Berlin. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-31.pdf (accessed June 2020)

12. DERA (2019). DERA Rohstoffliste 2019. DERA Rohstoffinformationen 40. Berlin ISBN: 978-3-943566-87-1 Access at https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-40.pdf? (accessed June 2020)

13. Ellen McArthur Foundation (2013). Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf (accessed May 5, 2020)

14. Erdmann L and Graedel, TE (2011). Criticality of non-fuel minerals: a review of major approaches and analyses. Environ. Sci. Technol. 45. https://doi.org/10.1021/es200563g

15. EU Commission (2010). Critical Raw Materials for the EU: Report of the Ad-hoc Working Group on Defining Critical Raw Materials. Available online: https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/system/files/ged/79%20report-b_en.pdf (accessed June 2020)

16. EU Commission (2011). EU Directive 2011/65/EU Restriction of Hazardous Substances (RoHS 2) in Electrical and Electronic Equipment http://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm (accessed June 2020)

17. EU Commission (2020). A new Circular Economy Action Plan For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, The European Economic and social committee and the committee of the regions. https://ec.europa.eu/info/sites/info/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf (accessed April 20, 2020)

18. Fizaine F (2013). Byproduct production of minor metals: Threat or opportunity for the development of clean technologies? The PV sector as an illustration. Res. Pol. 38 (3). https://doi.org/10.1016/j.resourpol.2013.05.002

19. Frenzel M, Mikolajczak C, Reuter M, Gutzmer J (2015). Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium. Res. Pol. 52. https://doi.org/10.1016/j.resourpol.2017.04.008

20. Friege H (2012). Review of material recovery from used electric and electronic equipment: alternative options for resource conservation. Waste Manage. Res. 30 (9). https://doi.org/10.1177/0734242X12448521

21. Gaustard G, Krystofik M, Bustamante M, Badami B (2018). Circular economy strategies for mitigating critical material supply issues. Resour. Conserv. Recycl. 135. https://doi.org/10.1016/j.resconrec.2017.08.002

22. Graedel TE, Harper EM, Nassar NT, Reck BK (2013). On the materials basis of modern society, PNAS 112. 6295–6300, http://dx.doi.org/10.1073/pnas.1312752110

23. Graedel TE, Allwood J, Birat JP, Reck BK, Sibley SF, Sonnemann G, Buchert M, Hagelüken C (2011). Recycling Rates of Metals – A Status Report.. ISBN 978-92-807-3161-3. https://www.resourcepanel.org/reports/metal-recycling (accessed June, 2020)

24. Gunn G (2014). Platinum-group metals. Chapter 12 in Gunn (Ed).Critical Metals Handbook. John Wiley & Sons, Oxford. https://doi.org/10.1002/9781118755341.ch12

25. Hagelüken, C & Corti, CW (2010). Recycling of gold from electronics: Cost-effective use through 'Design for Recycling'. Gold. Bull. 43: 209. https://doi.org/10.1007/BF03214988

26. Hagelüken C, Meskers C (2010). Complex life cycles of precious and special metals. In: Graedel T, van der Voet E (Eds.) Linkages of Sustainability. MIT Press. ISBN: 0-262-01358-4. pp. 163-197

27. Hagelüken C (2014). Recycling of (critical) metals. Chapter 3 in Gunn G (Eds) Critical Metals Handbook. John Wiley & Sons, Oxford. https://doi.org/10.1002/9781118755341.ch3

28. Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, Walton A, Christensen P, Heidrich O, Lambert S, Abbott A, Ryder K, Gaines L, Anderson P (2019). Recycling lithium-ion batteries from electric vehicles. Nature. 575. https://doi.org/10.1038/s41586-019-1682-5

29. Holgersson BS, Steenari M, Bjoerkman C and Cullbrand K (2018). Analysis of the metal content of small-size waste electric and electronic equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resour. Conserv. Recycl. 133. https://doi.org/10.1016/j.resconrec.2017.02.011

30. Huisman J, Magalini F, Kuehr R, Maurer C, Ogilvie S, Poll J, et al. (2007). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Final report. http://ec.europa.eu/environment/waste/weee/pdf/final_rep_unu.pdf (accessed June 2020)

31. Huisman J, Leroy P, Tertre F, Söderman M, Chancerel P, Cassard D, Løvik A, Wäger P, Kushnir D, Rotter VS, Mählitz P, Herreras L, Emmerich J, Hallberg A, Habib H, Wagner M, Downes S (2017). Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report. http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf (accessed June 2020)

32. ITU International Telecommunication Union (2016). ICT Facts and Figures 2016. http://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx (accessed June 2020)

33. Izatt RM (2016). Metal Sustainability: Global Challenges, Consequences, and Prospects. Wiley and Sons. 552 pages. ISBN: 978-1-119-00910-8

34. Jowitt SM, Werner TT, Weng Z, Mudd G (2017). Recycling of the rare earth elements. Current Opinion in Green and Sustainable Chemistry https://doi.org/10.1016/j.cogsc.2018.02.008

35. Liedtke M and Huy D (2018). Rohstoffrisikobewertung – Gallium. DERA Rohstoffinformationen 35: 86 S.; Berlin. ISBN: 978-3-943566-50-5. https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_gallium-2018.pdf? (accessed June 2020)

36. Mathieux F, Ardente F, Bobba S, Nuss P, Blengini G, Alves Dias P, Blagoeva D, Torres De Matos C, Wittmer D, Pavel C, Hamor T, Saveyn H, Gawlik B, Orveillon G, Huygens D, Garbarino E, Tzimas E, Bouraoui F and Solar S (2017). Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, https://doi.org/10.2760/378123

37. Mudd G; Weng Z; Jowitt S A (2013). Detailed Assessment of Global Cu Resource Trends and Endowments. Econ. Geol. 2013, 108, 1163–1183. https://doi.org/10.2113/econgeo.108.5.1163

38. NSTC (2016). National Science Technology Council. CSMSC Assessment of Critical Minerals Report. https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf (accessed June 2020)

39. Nassar NT, Graedel, TE, Harper EM (2015). By-product metals are technologically essential but have problematic supply. Sci. Adv. 1. https://dx.doi.org/10.1126%2Fsciadv.1400180

40. Nelen D, Manshoven S, Peeters JR, Vanegas P, Hase N, Vrancken K, (2014). A multidimensional indicator set to assess the benefits of WEEE material recycling. Jour. of Clean. Prod. Vol 83. https://doi.org/10.1016/j.jclepro.2014.06.094

41. Pohl WL (2011). Economic Geology, Principles and Practice: Metals, Minerals, Coal and Hydrocarbons— an Introduction to Formation and Sustainable Exploitation of Mineral Deposits. 678 Pages. Wiley Blackwell. ISBN: 978-1-444-33663-4

42. Polak M, Drápalová L (2012). Estimation of end of life mobile phones generation: The case study of the Czech Republic. Waste Manag. 32(8). https://doi.org/10.1016/j.wasman.2012.03.028

43. Redlinger M, Eggert R, Woodhouse M (2015). Evaluating the availability of gallium, indium and tellurium from recycled photovoltaic modules. Sol. Energy Mater. Sol. Cells. 138. https://doi.org/10.1016/j.solmat.2015.02.027

44. Reimer M, Schenk-Mathes H, Hoffman M and Elwert T (2018). Recycling Decisions in 2020, 2030, and 2040—When Can Substantial NdFeB Extraction be Expected in the EU? Metals. 8(11). https://doi.org/10.3390/met8110867

45. Reck B and Graedel TE (2012). Challenges in Metal Recycling. Science. 337 (6095) 695. https://doi.org/10.1126/science.1217501

46. Reuter M and van Schaik A (2012). Opportunities and limits of recycling: A dynamic-model-based analysis. MRS Bulletin. https://doi.org/10.1557/mrs.2012.57

47. Reuter M A, Hudson C, van Schaik A, Heiskanen K, Meskers C, Hagelüken C (2013). Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the Inter-national Resource Panel.. ISBN: 978-92-807-3267-2. https://www.resourcepanel.org/reports/metal-recycling (accessed June, 2020)

48. Reuter M, van Schaik A, Gutzmer J, Bartie N, Abadias-Llamas A (2019). Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annu. Rev. of Mater. Res. 49. https://doi.org/10.1146/annurev-matsci-070218-010057

49. Sarath P, Bonda S, Mohanty S, and Navak S (2015). Mobile phone waste management and recycling: Views and trends. Waste Manag. 46. https://doi.org/10.1016/j.wasman.2015.09.013

50. Schrijvers D, Hool A, Blenginid GA, Chene WQ, Dewulf J, Eggert R, Ellen L, Gauss R, Goddin J, Habib K, Hagelüken C, Hirohatam A, Hofmann-Amtenbrink M, Kosmol J, Le Gleuherp M, Grohol M, Kur A, Lees MH, Liu G, Nansai K, Nuss P, Peck D, Reller A, Sonnemann G, Tercero L, Thorenz A, Wäger PA (2020). A review of methods and data to determine raw material criticality. Resour. Conserv. Recycl. 155. https://doi.org/10.1016/j.resconrec.2019.104617

51. Schulz KJ, DeYoung JH, Bradley DC, and Seal II RR (2017). Critical mineral resources of the United States— an introduction, In: Schulz, KJ, DeYoung, JH, Seal, RR, and Bradley, DC, (eds.). Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802A.

52. Schulz KJ, Piatak NM, and Papp JF (2017a). Niobium and Tantalum. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the United States - Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802M.

53. Silveira, AVM, Fuchs, MS, Pinheiro DK, Tanabe, EH, Bertuol DA (2015). Recovery of indium from LCD screens of discarded cell phones. Waste Manag. 45. https://doi.org/10.1016/j.wasman.2015.04.007
54. Statista (2019a). Dossier Smartphones. Statista Study ID 12856, sources after IDC (Global Mobile Phone tracker); Gartner. https://de.statista.com/statistik/studie/id/3179/dokument/smartphones-statista-dossier/ (accessed June 2020)
55. Statista (2019b). Dossier Mobiltelefone. Statista Study ID 6242. Sources after Gartner; ITU. https://de.statista.com/statistik/studie/id/6242/dokument/mobiltelefone-statista-dossier-2012/ (accessed June 2020)
56. Tanskanen P (2013). Management and recycling of electronic waste. Acta Materialia. 61 (3). https://doi.org/10.1016/j.actamat.2012.11.005
57. Tercero L and Soulier M (2018). Defining regional recycling indicators for metals. Res Con Recycl. https://doi.org/10.1016/j.resconrec.2017.10.022
58. Thomas Jefferson National Accelerator Facility (2020). Office of Science Education. Crustal Abundances. http://education.jlab.org/itselemental/ele037.html (accessed June, 2020)
59. USGS United States Geological Survey (2017). Critical Minerals of the United States. https://www.usgs.gov/news/critical-minerals-united-states (accessed May 5, 2020)
60. USGS (2010). Economic Filters for Evaluating Porphyry Copper Deposit Resource Assessments Using Grade-Tonnage Deposit Models, with Examples from the U.S. Geological Survey. Global Mineral Resource Assessment. Download at https://pubs.usgs.gov/sir/2010/5090/h/sir2010-5090h_text.pdf (accessed May 5, 2020)
61. Van Gosen BS, Verplanck PL, Seal RR, Long KR, and Gambog J (2017). Rare-earth elements, chap. O of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States— Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. O1– O31, https://doi.org/10.3133/pp1802O
62. Wäger, P.A., Widmer, R. and Stamp A. (2011). Scarce technology metals – applications, criticalities and intervention options. Federal Office for the Environment, Bern.
63. Zientek M, Loferski PJ, Parks H, Schulte RF, and Seal RR (2017). Platinum-group elements. In Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the United States. https://doi.org/10.3133/pp1802N

5.8. Supplemental Material

Table 1: Range of mass fractions of each element from investigated smartphone manufacturers (n = 3). 'Min' corresponds to the lowest determined fraction, 'Max' corresponds to the highest determined fraction from investigated smartphones. Data is sorted by descending average mass fraction.

	Min	Max	Average
Element	[mg/kg]	[mg/kg]	[mg/kg]
Fe	38184	275146	139359
Si	61222	106224	84700
Mg	1747	157939	71257
Cu	33779	90781	57890
Al	20211	108966	57588
Ni	6533	34546	22412
Cr	26	52844	17828
Sn	3748	7796	5675
Zn	971	13026	5227
Sr	836	5841	4070
Ba	2313	3741	3164
REE (sum)	2640	2843	2749
W	218	5856	2359
Mn	636	2665	1629
Ti	798	1370	1017
Co	251	841	449
Ta	250	444	362
Zr	124	523	346
Mo	127	625	330
Au	116	177	155
V	33	203	110
Ag	61	122	101
Pb	64	117	86
Ga	36	100	73
Nb	28	53	38
As	25	36	30
In	19	28	23
Pd	13	19	17
Li	6	12	8
Hf	4	7	6
Bi	3	7	5
Pt	2	9	5
Sb	2	7	4
Ge	2	6	3

Details for section **5.3** and **Figure 5.4**:

For the selected metals Au, Cu, Pd, Pt, and by-products Co, Ga, Ge, In, REE, and Ta their geological occurrence, their ore grade in current mine sites, the current recycling aspects, and their usage/content in smartphones is summarized in the following paragraphs.

Gold (Au)

Gold mining is largely diversified and production is from almost 860 producing mines, with the 20 largest mines covering only 20 % of global production. Artisanal mining is a large source for Au but no exact annual production data exists. Thus, data given only comprises official mine production. Mudd et al. (2012) summarized Au deposits ranging from 0.38 mg/kg at Bingham Canyon (a Cu-Au-Ag Mo porphyry deposit in the USA) to 24.88 mg/kg at Gosowong (an epithermal deposit in Indonesia), with most deposit grades between 0.8 to 5 mg/kg. These examined 38 mines covered one third of 2010 annual production with an average ore grade of 1.4 mg/kg. Open pit mines can already be profitable with lower grades as low as 0.1 mg/kg, while underground mines (such as Witwatersrand Basin) usually have higher grades (>5 mg/kg). Mudd et al. (2012) calculated the current average Au ore grade for various countries: Australia with approximately 2 mg/kg; Canada and South Africa ranging from 2 to 3 mg/kg.

Recycling of gold adds approximately 25 % to the total supply, of which around 90 % originate from jewelry and 10 % from electronic scrap (WGC, 2019).

Gold in smartphones totals to 16.83 mg (155 mg/kg per device). 98 % of the measured Au are located on the PCB; the PCB separately contains 1080 mg/kg. Au is needed in miniature contacts in smartphones as it is non-corrosive and yet a very good conductor, which can be manufactured into extremely thin layers for Au-bonds (thin wires) where space is limited.

Cobalt (Co)

The total supply of cobalt including secondary resources comes from large-scale mining (LSM, 75 %), artisanal mining (ASM, 13%), recycling (10 %), and from slacks and tailings (2 %) (Al Barazi, 2018).

Co from industrial LSM sources is mainly mined as a by-product: approximately 65 % of the Co from LSM is derived from the production of Cu and 35 % from the production of Ni. The Cu production from oxides (55-60 % of LSM) have a grade of around 0.4 % Co, the sulfides (5-10 % from LSM) contain ~0.58 %. The nickel-laterites (30 % of LSM) contain ~0.1 % Co, the remaining 5 % from Ni-sulfides contain ~0.13 % Co.

In 2017, almost 60 % of the Co-production came from the DR Congo. ASM is a large uncertainty factor for Co-production, with legal ASM and illegal ASM taking place, and no numbers exist for the exact output or for the Co content. Thus, only LSM data is given in this study. The two largest mine sites, Mutanda (at grade 0.662 % Co) and Tenke Fungurume (at grades 0.318 % Co), located in DR Congo, already cover 41 % of total cobalt mine production in 2017 (Al Barazi, 2018).

Recycling of Co comes from various sources, such as catalysts, scrap, alloy and magnets, but also from batteries, with Lithium-Ion-batteries and their Co-cathode being of increased interest.

Co in smartphones (without the battery) totals 50.25 mg (449 mg/kg for entire device), with 11 % located on the PCB; main parts of Co are found in the vibration motor and in permanent magnets; small amounts are alloyed in cover-plates and frames.

Copper (Cu)

Copper ranks third after steel (iron) and aluminum in world metal consumption. There is a wide range of mineral deposit types that host significant Cu resources and reserves. Mudd et al. (2013) summarized 730 projects (a total of 363.3 billion tons Cu produced over several years) at an average grade of 0.49 % Cu. Most of the large sites that have been mined in the past 100 years have Cu grades between 0.1 % and 1 %, with some sediment hosted and volcanogenic massive sulfide (VMS)-sites up to 3 %; 72 % of the projects have copper grades below 1 %. Seven of the ten largest sites today are large porphyry copper deposits (Mudd et al., 2013). Some of the Cu sites also host gold, with grades between 0.1 up to 1.82 g/t Au; e.g., the Grasberg mine in Indonesia is the second largest Cu but also the largest Au mine. The top 20 Cu mine sites by output capacity produce about 43 % (8,700,000 t Cu) of the world's primary Cu (ICSG, 2019).

Recycling of Cu is widely facilitated and EOL- recycling rates for Cu are with over 50 % higher than for other metals. Recycled Cu adds with around 4,000,000 t Cu 17 % to the total global supply (ICSG, 2019).

In smartphones, Cu is the fifth most abundant metal with a total of 6.6064 g (57,890 mg/kg for the total device); it is the foremost metal in the PCB (390,548 mg/kg). 98 % of the measured Cu is located on the PCB; small amounts can be found in thin wires and other conductors.

Gallium (Ga)

Gallium metal is derived (80 %) as a by-product in bauxite for aluminum production; lesser amounts of gallium metal are produced as by-products zinc production. Some coal-deposits may also contain Ga as a minor metal (Liedtke and Huy, 2018).

In Bauxite, the average Ga-content is 57 mg/kg (Schulte and Foley, 2014; Liedtke and Huy, 2018). The average deposits lie between 5-142 mg/kg Ga, most deposits grade between 20-70 mg/kg. Cd-Pb-Zn ores average 60 mg/kg Ga, but can range between 1 to 1600 mg/kg. In general, concentrations in most sphalerite ores rarely exceed 100 mg/kg Ga (Schulte and Foley, 2014). Carbonate-hosted Pb-Zn MVT (Mississippi Valley-type) deposits, e.g., the Apex Mine in Utah (1480 mg/kg Ga), was mined for Ga (and Ge) as a primary product until 1990. MVT deposits of similar type are currently under exploration, e.g. in the cordillera oriental of Peru (Mondillo et al., 2018)

Less than 10 -15 % of the Ga in bauxite and Zn ores is recovered (Frenzel et al., 2015).

Recycling of Ga mainly takes place from production scrap as recovery from EOL-Scrap is not economically feasible and is below 1 % (Nassar et al., 2015; Liedtke and Huy 2018).

In smartphones, total Ga content is 8.37 mg (82 mg/kg per device). Ga is used as arsenide (GaAs) or nitride (GaN) for the production of highly specialized integrated circuits, LEDs and transistors; Ga ia also used for manufacturing of permanent magnets (Liedtke and Huy, 2018). About 30 % of the measured Ga is located on the PCB, about 40 % is found in the permanent magnets and the rest is measured in coverplates and diminutive amounts in the housing.

Germanium (Ge)

Germanium occurs as a by-product in a variety of deposit types that contain Cu, Au, Pb, Ag, and Zn (Melcher & Buchholz, 2014). Ge is primarily recovered from the leaching of Zn residues or coal ash followed by precipitation of a Ge concentrate. The main source (estimated 60 % of worldwide production (Frenzel, 2017) for Ge is Zn-ore (sphalerite), and about 40 % originate from the recovery of coal fly ash.

The average concentrations of Ge in sphalerite range up to 249 mg/kg. The SEDEX Fankou Mine in China contains from 30 to 170 mg/kg Ge. Ge averages 68 mg/kg in bulk samples in the Kipushi Zn-PbCu deposit in the DR Congo. The Gordonsville Elmswood Zn mine in Tennessee (USA) currently produces Ge with a grade of 20 mg/kg as a byproduct. China is the major producer of Ge, where Ge-rich coal seams interbedded with host rock are processed, e.g., in the largest production site Xilingol in Inner Mongolia, where they occur at a grade of up to 850 mg/kg Melcher and Buchholz, 2014; Shanks et al., 2015).

About 30 % of global germanium production is derived by recycling from new scrap (production scrap), but recycling from EOL is low (<1 %) due to dissipation of Ge in products (Nassar et al., 2015).

In smartphone, the total Ge content is low at 0.35 mg (3 mg/kg for complete device). 60 % of the measured Ge are on the PCB (12 mg/kg for PCB), the rest was found in miniscule amounts in the coverplates as alloy.

Indium (In)

Indium is solely mined as a by-product during the refining process, mainly from copper and zinc sulfides. Waste products generated during the refining process, such as dusts, fumes, residues, and slag, are collected and treated for the recovery of In. A large section of In is produced in southern China from volcanogenic massive sulfide (VMS) and sedimentary exhalative (SEDEX) deposits, and much of the remainder is produced from zinc concentrates from MVT deposits (Shanks et al., 2015). Ores of metals other than zinc (especially some copper-tin ores), coal deposits, and fly ash from coal burning, have potential significant concentrations In and might become important future sources. The solely indium-producing Toyoha Mine in Hokkaido Prefecture, Japan, closed in 2006 (Schwarz-Schampera, 2014).

The concentration of In is highest within chalcopyrite ores, where concentrations are twice as high as in sphalerite ores, yet sphalerite remains the most important In-bearing mineral for by-production (Schwarz-Schampera, 2014). Roskill (2010) assumes that sphalerite ores contain 67 % Zn and 15-50 mg/kg In, although they assume that the actual amount of In contained in the zinc ores may be much higher than estimated. In general, In content is thought to be between 10 – 100 mg/kg (Schwarz-Schampera, 2014). In practical terms, only approximately 30% of the total mined In is extracted during the refinery process of Cu and Zn ores (Lokanc et al., 2015).

Recycling of In is mainly done for production scrap from sputter targets. Due to high dispersion, EOL recycling is below 1 % (Nassar et al., 2015).

The measured In content in smartphones makes up a total average of 2.58 mg (23 mg/kg for total device), with the major part (86 %) located on the PCB (140 mg/kg for PCB) and the remaining 14 % in the display. When investigating the display as one compartment separately, the content of In is 14 mg/kg, with one layer containing up to 89 mg/kg In. The display can, depending on type, contain of up to 8 layers of different glass-types and foils which are partly glued together and are hard to separate manually.

Palladium (Pd), Platinum (Pt)

The PGEs (platinum group elements) comprise platinum and palladium, which usually occur together, as well as the chemically similar elements rhodium, ruthenium, iridium, and osmium. The average grade for mined PGE ores varies from 5 to 15 mg/kg (Schmidt, 2015).

Since 1900, about 90 percent of the Pt and Pd production came from two main regions: South Africa and Russia (Zientek et al., 2017). The conduit-type deposits of the Noril'sk-Talnakh area in Russia are associated with an enormous outflow of mafic magma that formed the Siberian Traps—the largest continental flood basalt province on Earth. The South African deposits are related to the Bushveld complex, a vast mass of igneous rock that underlies an area of approximately 69,000 km^2 in South Africa, which has several igneous suites.

Recycled Pd and Pt provide a significant proportion of the world's total supply (31 %) and are mainly obtained through the recycling of catalytic converters from chemical processes, EOL-vehicles, jewelry, and electronic equipment (Johnsons Matthew, 2018).

In smartphones, Pd totals 1.91 mg per device (17 mg/kg for total device) with 99 % of Pd located on the PCB in contacts and capacitors (126 mg/kg Pd for PCB). Platinum in smartphones totals 0.48 mg (5 mg/kg for total device), with most Pt on the PCB in contacts (13 mg/kg for PCB).

Rare Earth Elements (REE)

Rare earth elements, apart from the element promethium, are not rare in terms of average crustal abundance, but concentrated and economic deposits of REEs are unusual. Due to their large atomic radii they do not occur in many of the more common rock forming minerals (Van Gosen et al., 2017). Ce and La are the more abundant REEs in earth's crust with 63 mg/kg and 20 mg/kg respectively, and Tb, Ho and Tm are less abundant with 0.3-0.8 mg/kg, with the other REEs in between. Geologically, many of the world's REE deposits are associated with carbonatites, which are igneous rocks derived from carbonate-rich magmas. REE deposits enriched in light REE (elements La, Ce, Pr, Nd, Pm, Sm, Eu, Gd) occur mostly with the minerals bastnäsite [(REE) CO_3F], monazite [(REE, Th) PO_4] and loparite (REE,Na,Ca)(Ti,Nb)O_3; ion-adsorption clay deposits in southern China are the world's major primary sources of the heavy REEs (elements Tb, Dy, Ho, Er, Tm, Yb, Lu, plus Y). In geological reflections, the element Sc is not counted to LREE or HREE due to its different occurrence in deposits. REE have been in the public focus since 2010 when China, then dominating production with over 95 %, restricted their export of REE. China still leads the global extraction of rare-earth oxides from the ores, it also specializes in the downstream activities, i.e., the separation and processing into the individual rare-earth metals, and the production of rare-earth permanent magnets (Jowitt et al., 2017). Reported grades are 4.1 – 6.0 % REE content for Bayan Obo in China, the largest REE deposit, sourcing 80 % of global LREE, with the primary ore being Fe. REE grades are at 7.9 % at Mount Weld in Australia, ranging between 0.1-10.0 %; Mountain Pass in the USA grades at 7.98 %, which used to be the main global REE source in the 1960-1990s and reopened in 2018, yet processing of their REE still takes place in China (BGS 2011; Van Gosen et al., 2017).

Ion-adsorption clays in southern China grade at 300 to 2,000 mg/kg REE but are only profitable because of their relatively low-cost mining, their chemical extraction methods, and less stringent environmental restrictions (Van Gosen et al., 2017).

REE from recycling mainly sources from production processes (e.g., new scrap of magnet production residues) and industrial waste; only around 1 % of the REE are recycled from EOL due to low total content in complex products (Binnemans et al., 2013; Jowitt et al., 2017).

The total amount of REE in smartphones was measured with 303.39 mg, with Nd accounting for 70 % of the REE with a total of 211.81 mg, followed by Pr (65.11 mg), Dy (12.10 mg), and Gd (9.01 mg). 97 % of the measured REE are located in the magnets of loudspeaker, vibration motor, and camera. Only miniscule amounts of REE were found in the display.

Tantalum (Ta)

Tantalum has very similar physical and chemical properties as niobium (in earlier times called columbium). Ta minerals of economic importance are those of the columbite-tantalite group, the abbreviation “coltan” (which is commonly used for tantalum ore of African origin) has been connected to human rights issues such as child labor and powering the civil war (Amnesty International, 2017). In 2016, artisanal mining accounted for 63 % of the global Ta production, conventional mining for 28 % and processing of tin slags (a by-product of tin mining and smelting) accounted for the remaining 9 % (Damm, 2018). Typical grades vary between 0.01 to 1 % Ta_2O_5, with average Ta grades around 0.02 to 0.05 % Ta, e.g., in Wodgina, a large pegmatite deposit in Australia (Schulz et al., 2017a). Especially for artisanal mining in the Great Lakes Region such as Rwanda, DR Congo and Burundi, there is no data available for grades of Ta contained in stream sediments or soils. Artisanal mining sites are vastly distributed, sometimes unregulated and intransparent to track; approximately 80,000 people are working in the Great Lakes Region in artisanal mining of Ta, Sn and W. Probing and detailed measuring of deposits to determine averaged grades has not yet professionally taken place (Schulz et al., 2017a; Damm, 2018).

Of the seven producing conventional mines in 2016, two mines are hosted in alkaline igneous complexes, the others are hosted in rare-metal-pegmatites. Only for three of these mines, data for Ta grades are available (most of the ores are processed physically at or near the sites and the separated Ta is already sold as concentrates); Schulz et al. (2017a) estimates that the grades are mostly below 0.04 % Ta.

Tantalum recycling mostly takes place from new scrap, generated during the manufacturing of cemented carbide, electronics, and superalloys. Recycling from EOL is low, Ta only occurs in low contents in complex matrices that are too complicated to recycle (Damm, 2018).

In smartphones, Ta content totals 40.20 mg (362 mg/ kg per total device), with 93 % on the PCB in microcapacitors and as alloy for special parts (37 mg and 2385 mg/kg for PCB itself).

5.8.1. References

Al Barazi S (2018). Rohstoffrisikobewertung – Kobalt. DERA Rohstoffinformationen 36: 120 S.; Berlin. 978-3-943566-48-2. Access at https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-36.pdf?__blob=publicationFile&v=2 accessed May 2020

Binnemans K, Jones BT, Blanpain B, Gerven T, Yang Y, Waltone A, Buchert M (2013). Recycling of rare earths: a critical review. J. Clean. Prod. Vol 51. https://doi.org/10.1016/j.jclepro.2012.12.037

Damm S (2018). Rohstoffrisikobewertung – Tantal – DERA Rohstoffinformationen 31: 82 S.; Berlin. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-31.pdf?__ accessed May 2020

Frenzel M, Mikolajczak C, Reuter M, Gutzmer J (2015). Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium. Res. Pol. 52. https://doi.org/10.1016/j.resourpol.2017.04.008

ICSG International Copper Study Group (2019). Statistic data for Copper Production. https://www.icsg.org/index.php/statistics/selected-data accessed May 2020

Johnson Matthey (2018). PGM Market Report May 2018. http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm_market_report_may_2018.pdf accessed July 2020

Jowitt SM, Werner TT, Weng Z, Mudd G (2017). Recycling of the rare earth elements. Current Opinion in Green and Sustainable Chemistry https://doi.org/10.1016/j.cogsc.2018.02.008

Liedtke M and Huy D (2018). Rohstoffrisikobewertung – Gallium. DERA Rohstoffinformationen 35: 86 S.; Berlin. ISBN: 978-3-943566-50-5.

https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_gallium-2018.pdf?__blob=publicationFile&v=2 accessed July 2020

Lokanc M, Eggert R, Redlinger M (2015). The Availability of Indium: The Present, Medium Term, and Long Term. United States NREL. https://doi.org/10.2172/1327212

Melcher T & Buchholz P (2014). Germanium. Chapter 8 in Gunn G: Critical metals handbook. John Wiley & Sons, Oxford. https://doi.org/10.1002/9781118755341.ch8

Mondillo N, Arfè G, Herrington R (2018). Germanium enrichment in supergene settings: evidence from the Cristal nonsulfide Zn prospect, Bongará district, northern Peru. Miner. Deposita. 53, 155–169 (2018). https://doi.org/10.1007/s00126-017-0781-1

Mudd G, Giurco D,Mohr S,Mason L (2012). Gold resources and production: Australia in a global context. Monash University and University of Technology, Sydney. http://cfsites1.uts.edu.au/find/isf/publications/muddetal2012goldresourcesproduction.pdf accessed May 2020

Mudd G; Weng Z; Jowitt S A (2013). Detailed Assessment of Global Cu Resource Trends and Endowments. Econ. Geol. 2013, 108, 1163–1183. https://doi.org/10.2113/econgeo.108.5.1163

Schulte RF and Foley NK (2014). Compilation of gallium resource data for bauxite deposits. USGS report. https://doi.org/10.3133/ofr20131272

Nassar NT, Graedel, TE, Harper EM (2015). By-product metals are technologically essential but have problematic supply. Sci. Adv. 1. https://dx.doi.org/10.1126%2Fsciadv.1400180

Roskill (2010). Indium. Global Industry, Markets, Outlook. Report. ISBN: 978 0 86214 558 3

Schmidt M (2015). Rohstoffrisikobewertung – Platingruppenmetalle. DERA Rohstoffinformationen 26: 156 pages., Berlin. https://www.bgr.bund.de/DERA/DE/Downloads/studie_Platin_2015.html accessed May 2020

Schulz KJ, Piatak NM, and Papp JF (2017a). Niobium and Tantalum. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the United States - Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802M.

Schwarz-Schampera U (2014). Indium. Chapter 9 in Gun (Ed) Critical Metals Handbook. John Wiley & Sons, Oxford. https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118755341.ch9

Shanks WCP, Shanks III, Kimball BE, Tolcin AC, and Guberman DE (2017). Germanium and Indium. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR,II (2017). Critical mineral resources of the United States. https://doi.org/10.3133/pp1802I

Van Gosen BS, Verplanck PL, Seal RR, Long KR, and Gambog J (2017). Rare-earth elements, chap. O of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States— Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. O1– O31, https://doi.org/10.3133/pp1802O

WGC World Gold Council (2019). Gold statistics. www.gold.org accessed May 2020

WPIC World Platinum Investment Council (2019). Platinum statistics. https://platinuminvestment.com/supply-and-demand/platinum-quarterly accessed May 2020

6. Educational outreach study

6.1. Importance of social factors

In the previous chapters, it was described that smartphones are of interest due to their wide usage with high sale numbers, with metal constituents of over 50 metals, yet often unsustainable raw materials sourcing, and problematic end of-life management. The latter is to a certain extent - additionally to recycling technologies - much dependent on consumers: Not only are consumers the ones to decide which and how many devices to purchase, they also decide about the length of the use phase, and most importantly about the disposure of smartphones at the end of their use phase.

Consumer behavior for smartphones is often cited as a prime example for unsustainable raw material consumption (e.g., Graedel et al., 2011), since devices are averagely replaced after about 18 to 24 months, although they are still functional (Bitkom, 2020). The storing of smartphones after they are no longer used has been one issue as to why recycling rates of smartphones are low. Consumers recognise lasting value in their used mobile devices, no matter if it is for personal memorabilia or perceived material value or as a spare device for, e.g., a vacation (Nodmann et al., 2014). The fear of lost and/or misused personal data adds to keeping the devices stored at home. Smartphones are small in size and can be easily stored for longer time periods than other larger electr(on)ic devices; consequently, the hoarding of smartphones is a larger issue than for other EEE in general (Huisman et al., 2017). The accessibility to recycling has also been detected as an issue, as smartphones, just as all other EEE devices, are not allowed in the household trash, indicated by the crossed trash bin on each electronic device. They need to be taken to communal recycling centres or to electronics selling points to be correctly disposed of, which might often feel time consuming for users. In general, people are often not sure where to dispose their smartphones correctly (without having private data tempered with) and this lack of knowledge has also been termed as a decisive factor (Nordmann et al., 2014). Furthermore, smartphones have a high reuse value and there is a large market for used smartphones. From a sustainability point of view, a long use phase is favourably, and the longer products and materials are kept in use, the more resource efficient their usage becomes (Teehan & Kandlikar, 2014).

For the typical mobile device, consumer have little to no incentive to recycle the device, as they are usually not aware of the value of the extractable materials or benefit in any way from recycling. With this lack of incentive for consumers and apparently time consuming recycling options, how and where mobile devices are recycled often depends heavily on regulatory policies and mechanisms (or lack thereof) within each country to handle WEEE.

The OECD states in 2010 that the education of consumers on appropriate management practices of used and end-of-life mobile devices is of significant importance (OECD, 2010) to ensure a more sustainable life cycle for smartphones. Young adults and youth are the main driver for electronic device sales, with a coverage of 98 % for over 14 year olds (Nordmann et al., 2014). This was set as the main target group.

6.2. Study setup

Chapters 7 and 8 summarize the research on social behavior and incentives in regards to smartphones and their recycling.

6.2.1. Theoretical research on consumer behavior

The factors for consumers to determine their recycling management were investigated by examining the acceptance of mobile phone return programs, using the Technology Acceptance Model and multiple case studies. **Chapter 7** describes the theoretical research to understand recycling behavior of consumers. For improvement of recycling rates, recommendations for actions are provided.

6.2.2. Teaching kit

The target group of youth over 14 years is easiest reached by schools and museums (e.g., Breslyn et McGinnis, 2012). Information for teachers on the topic was scarce, thus a hands-on teaching module with an accompanying brochure of 120 pages was developed, equipped with pre-made worksheets and background information for teachers for the direct implementation in classrooms; all materials were available at the Natural History Museum Vienna (nhm). Teacher workshops were conducted all over Austria (one in each federal state) to foster interdisciplinary implementation of the topic into the curriculum.

The teaching kit has been adapted, modified and reproduced several times. The general content was modified only slightly. Most of the kits were sent to multiplicators (museums, other education or teaching institutions) and some of them still provide the boxes for loan. **Chapter 8** summarizes the setup of the study and the development of the teaching module.

The first kit from the nhm in Vienna was produced 1000 times in 2011, followed by another 1500 boxes in 2012. It was accompanied by a teacher brochure of 72 pages, which could be ordered from the nhm shop (Bookhagen, 2012). The box has also been implemented in a larger teaching suitcase of the Elektro-Altgeräte Koordinierungsstelle Austria, which still operates Austria-wide in schools.

The “Handy-Rohstoffbox” contains eleven raw materials, representative for some of the metals and materials used for the production of mobile phones:

- copper ore (chalcopyrite)
- tantalum ore (tantalite)
- quartz (representing glass)
- pure polysilicon (for silicon in chips)
- lithium ore (lepidolite)
- aluminum ore (bauxite)
- iron ore (magnetite)
- gold flakes
- clay (bentonite)
- plastic
- bituminous shale (representative for kerogen/ crude oil (which could not be used in a school box due to safety reasons)

(In the following boxes, plastic and pure silicon were dismissed due to availability.)

Figure 6.1: *The first teaching box and its content by nhm.*

Figure 6.2*: The second teaching kit from the Year of Science 2012 with the adapted identification game.*

The second teaching kit was produced for the Year of Science 2012 (Wissenschaftsjahr 2012: Die Rohstoff-Expedition) of the German Federal Ministry for Education and Science (BMBF, 2012). The material was slightly adapted (the box contains nine raw materials plus an accompanying identification game) and graphically updated. 2000 boxes (plus an additional 500 boxes due to high demand in 2013) were produced by the author with the help of students. The teaching brochure was adapted and implemented together with other material of the Rohstoff-Expedition by Springer as a book in 2014 (Nordmann et al., 2014). Commercial production of the teaching kit by Springer failed due to high production and preparation cost of the raw materials (labelling and packing of each single raw material is too elaborate for commercial production).

The third teaching kit was adapted by the Telekom in 2014 and produced 240 times.

***Figure 6.3** and **6.4**: Third and fourth teaching kits, both in cooperation with Telekom and others.*

The fourth teaching kit was adapted in 2016 by the German ministry of Saarland and DERA (BGR), together with several sponsors such as Telekom, Brot für die Welt etc.; it was produced 250 times. The website www.handy-aktion.de is still online, other partners such as the ministry of Bavaria and North Rhine Westphalia joined in 2017 and 2018, and the box and the accompanying teaching material are still available for schools to borrow.

As of summer 2020, via the website of the BMBF, on average one or two inquires per month from teachers asking for the box still reach the author.

6.3. References

Bitkom 2020, Press statements: Germans hort 200 million mobile phones https://www.bitkom.org/Presse/Presseinformation/Deutsche-horten-fast-200-Millionen-Alt-Handys accessed July 2020

BMBF Bundesministerium für Bildung und Forschung (2012). Zukunftsprojekt Erde: Die Rohstoff-Expedition. https://www.wissenschaftsjahr.de/2012/die-rohstoff-expedition/die-rohstoff-expedition/rohstoffbox.html

Bookhagen B (2012). Rohstoffkoffer: Was steckt im Handy? LehrerInnenbroschüre. 76 S. Verlag Naturhistorisches Museum Wien, ISBN 978-3-902421-73-9

Breslyn, W., & McGinnis, J. R. (2012). A comparison of exemplary biology, chemistry, earth science, and physics teachers' conceptions and enactment of inquiry. Science Education, 96(1), 48-77.

Graedel TE, Allwood J, Birat JP, Reck BK, Sibley SF, Sonnemann G, Buchert M, Hagelüken C. (2011). Recycling Rates of Metals – A Status Report. ISBN 978-92-807-3161-3. https://www.resourcepanel.org/reports/metal-recycling accessed July 2020

Huisman J, Leroy P, Tertre F, Söderman M, Chancerel P, Cassard D, Løvik A, Wäger P, Kushnir D, Rotter VS, Mählitz P, Herreras L, Emmerich J, Hallberg A, Habib H, Wagner M, Downes S (2017). Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report to EU Commission. http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf accessed July 2020

Nordmann J, Welfens MJ, Fischer D, Nemnich C, Bookhagen B, Bienge K, Niebert K (2014). *Die Rohstoff-Expedition, Entdecke, was in (deinem) Handy steckt*. Springer Spektrum. Didaktik der Naturwissenschaften, Berlin.

OECD (2010). Case Study on Critical Metals in Mobile Phones (and 2017 Update) http://www.oecd.org/env/waste/Case%20Study%20on%20Critical%20Metals%20in%20Mobile%20Phones.pdf

Teehan P & Kandlikar M (2014). Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products (2013). Environmental Science & Technology. 47(9):3997–4003 https://doi.org/10.1021/es303012r

7. Acceptance of mobile phone return programs: A case study based analysis

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Published **2013 in ICT4S**: Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich. pages 59-65 DOI: http://dx.doi.org/10.3929/ethz-a-007337628

Abstract

The need of recycling obsolete mobile phones has significantly increased with the worldwide propagation of mobile phones and their inherent rapid turnover. In this article, we examine the acceptance of mobile phone return programs by using the Technology Acceptance Model and multiple case studies. Our findings can provide valuable recommendations for the setup of future mobile phone return programs.

7.1. Introduction

The increasing utilization and proliferation of information and communication technology (ICT) has drawn attention to the related economic and environmental sustainability effects [2][16] [40], especially when it comes to end-of-life management of the devices as stated in the WEEE-directive [39]. Each year, approx.

560 thousand tons of ICT waste is being collected in Europe [11]. Mobile phones, like computers and other ICT devices, contain many valuable and rare metals [15][23][25][27][32]. Due to the large quantity of mobile phones sold worldwide, the relatively small constituent per single device total to a significant amount of highly valuable, non-renewable resources [32]. Moreover, incorrect disposal of mobile phones can release toxic leftovers into the environment [31][32][39] and pose potential health risks [30]. Nevertheless, mobile phone recycling still only accounts to a few percentage of recycled material [23][31].

Studies show that substantial amounts of unused mobile phones are being stored in people's drawers [3]. To increase the return rates, organizations and institutions have implemented various mobile phone return programs. Some of the programs are more successful than others. The success rate highly depends on the acceptance of a program by the mobile phone owners. Revealing the drivers and barriers influencing the acceptance of a mobile phone return program would help developing more successful mobile phone return programs. This article therefore aims to answer the research question:

Which factors explain the acceptance of mobile phone return programs?

To answer this question we analyze mobile phone return programs and their accomplishments from various countries. The theoretical basis is provided by a modified version of the Technology Acceptance Model (TAM) [7]. We assess the possibility to transfer the factors of TAM to explain acceptance of mobile phone return programs. Results of this study can help to enhance future projects and thereby increase sustaining valuable resources.

7.2. Related research

7.2.1. Recycling and return programs

For this paper, the term “return program” takes all actions into account where mobile phones can be returned to ensure reuse or their proper recycling. Mobile phone return programs have different scopes, time frames, execution models and participating groups, e.g. ranging from charity events to bridging information and awareness for resources programs.

Although electronic waste recycling is a relatively new issue that evolved over the past years, research on determining the operative factors for recycling programs started in the 1980s and 1990s [12] [37]. According to [12], the success of return programs depends much on the policies chosen, how they are selected, and how they are implemented. Lacking knowledge is seen as one important barrier that prevents the separation of waste [5]. [17] summarize results of previous literature and identify the following variables as factors of recycling behavior: extrinsic incentives, intrinsic incentives, internal facilitators, and external facilitators.

Compared to other electronic waste, the recycling chain of mobile phones seems to be especially wedged when it comes to customers returning the mobile phone to any type of take back program (see for example Tanskanen and Butler [28]).

7.2.2. Basis of the technology acceptance model

This paper uses TAM to investigate the acceptance of mobile phone return programs. An adopted model of the Unified Theory of Acceptance and Use of Technology (UTAUT) provides the theoretical background to increase the expressiveness of our results. The UTAUT was developed by [34] and evolved from previous versions of the original TAM 1 [7] and the later TAM 2 [36] version. The TAM concepts are well-known and widely applied in information systems (IS) research literature, articles of highly rated scientific journals [19] and proceedings of actual IS conferences, for example [18].

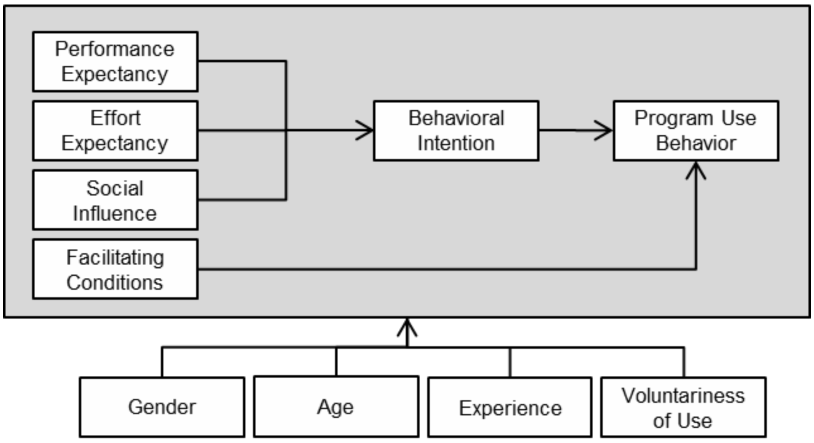

Figure7.1*: Theory of Acceptance and Use of Mobile Phone Return Programs Based on [34]*

The TAM models describe why people use certain technologies. Their original objective was to explain the acceptance of computer technology. But the concept has proven to be applicable to various IT related topics, e.g., explaining the acceptance of cloud computing [26].

The model can be used both for explanations and forecasts [7]. A characteristic of the model is the high level of abstraction and the consequent low number of model variables. For our research we apply the latest TAM concept, the UTAUT to the scope of mobile phone return programs. Based on the original UTAUT the following factors are used to explain the acceptance of mobile phone return programs (see Figure 1) [33]:

- Performance expectancy: The degree to which an individual believes that using the system will help him or her to attain a personal objective, such as environmental protection
- Effort expectancy: The degree of ease associated with the use of the program
- Social influence: The degree to which an individual perceives that important others believe he or she should use the program
- Facilitating conditions: The degree to which an individual believes that an organizational and technical infrastructure exists to support program
- Behavioral intention: The degree to which a person has formulated conscious plans to perform or not perform some specified future behaviour

Gender, age, experience, and voluntariness of use serve as moderating variables. They affect the strength of the relation between the independent and the dependent variables [4].

7.3. Methodology

To answer the research question we use case study research. Case study research is a widely known and accepted research methodology in IS [8]. It generates insights by examining a phenomenon in its usual setting [5].

Case study research can be applied to describe phenomena, test theories or develop new theories and hypotheses [5][9]. This corresponds with the paper's objective to describe the phenomenon of varying acceptance of mobile phone return programs in multiple settings. Case study research employs various data collection methods, such as document and literature analysis, interviews, observations or questionnaires [8]. Our investigation is based on:

- A comprehensive market and media research regarding mobile phone return programs
- An extensive literature research
- An in-depth case study regarding the return program of the Austrian Ö3 Wundertüte (literally: "wonderbag") and two programs of the Deutsche Telekom (German Telekom).

These tasks were performed between October 2011 and Mai 2012. We avoided using a numerical numerical performance rating, instead, we will summarize the results from our case study as recommendations based on the UTAUT-concepts of Performance Expectancy, Effort Expectancy, Social Influence and Facilitating Conditions. Due to the limitations of case study research our findings demand further validation through quantitative and qualitative research regarding the applicability of UTAUT to explain the acceptance of mobile phone return programs.

7.4. Findings

The data collected is shown in Table 1, listed by regional and worldwide return programs. We sorted the information by region and initiator, followed by a short description of the return process. We analyzed the programs by comparing the advertisement and effort used to introduce the return program, the year or period it took place and the incentive provided to make the return program attractive to users. The success of the programs was measured by the amount of returned mobile phones.

All European production and network companies take back mobile phones in their shops, as the WEEE directive has been asking since 2003 [39]. Therefore, this option is not explicitly listed in the table.

Charity includes all supportive actions (e.g., donations) for charity or social organizations. Environmental protection accounts to all actions taken to support environmental projects or active organizations.

In general, the governmental run or supported programs in the USA and UK seem to be relatively successful [13] [10], while company-run programs seem to be less effective, regardless of the incentives.

To deepen the comparison and give better implications, programs from two initiators were closer investigated about how the program was set up, and how well their collection of mobile phones was received: 1) The Austrian "Ö3 Wundertüte" [24] and 2) campaigns by the German Telekom Company [29][30].

Region	Initiator	Return Process	Incentives	Period	Collected mobile phones in Millions	Reference
Australia	Australian Mobile Telecommunications Association (AMTA)	Different campaigns, e.g. "MobileMuster", school challenges; drop-off points and free mail-ins	Environmental protection / Charity	1998-2011	6.31	Mobilemuster [1] [21]
Austria	Ö3 (federal supported radio station), partnered with Austrian Post, Caritas, Red Cross	Send free mail-in envelopes "Ö3 Wundertüte" ("wonderbags") before Christmas to 270.00 households in Austria; placed return boxes at partner's locations; expanded programs for schools as challenge	Charity / Contests in schools	2005-2012	2.5	Ö3 Radio [24]
UK	British Government; partnered with companies and organizations e.g. BBC	„Regenersis – Fonebak" / UK – very first recycling-program worldwide / Freepost service: customer will get money for the returned phone and select amount to donate (at least £5)	Charity / Money / Voucher for valuable phones	1999-2009	almost 20	Fonebak [13]
USA	EPA (US government Environmental protection agency), partners with retailers and companies	Drop-off and free mail-ins / at US westcoast: ATMs (automatic machines to give out voucher of estimated value)	Content information / environmental protection/ some voucher	2008 2007	11 14	EPA [10]
Germany	T Mobile	Free mail-ins; choice to donate phone or exchange for a shop-voucher / School competitions	Environmental protection / Charity	2009-2012	1.0	T-Mobile [29]
Germany	Vodafone	Company donates money for each returned mobile phone to social organizations in the area where mobile phone was returned / Customer can print out postage return label	Charity	2003-2012	1.0	Vodafone [38]
Germany	NABU (German nature protection coalition); Partner: E-Plus; former partner: Vodafone	Company donates up to 3€ per returned mobile phone for a project of the NABU / 200 collecting locations, free mail-ins (together with Vodafone and other partners)	Environmental protection	2006-2012	0.050	NABU [22]

***Table 7.1**: Overview of international mobile phones programs*

Ö3 Wundertüte

In Austria, the return-program supported by a federal run, over-regional radio station called the "Ö3 Wundertüte" has been running since 2005 for every year. The feedback has been very positive, and 2.5 million phones have been returned altogether (respecting that Austria has approx. 8 million inhabitants). Every year in late autumn, right before the advent season, envelopes are sent out to households throughout Austria with the prospect of donating money to two different charity organizations, helping needful people in Austria. For each returned phone a donation is made (three Euro for a functioning phone, 50 Cent for a non- working phone). It is reported that people even call throughout the year and ask whether they will again receive the envelope to send in their phone(s). In 2011, 467.000 mobile phones were collected in 275.000 envelopes.

We called Ö3 for a Telephone-Interview, asking for their practical experience and opinion why the return-program might have achieved a higher return-rate than other actions in other countries. Here, we summarize their opinion:

- Partners: They partnered with non-profit institutions well known for their reliability and trustworthiness and non- scandalous history
- Objective: The collection was primarily not communicated as a PR-activity but always made a point in being a charity-program; it was also visible and clear where the donations went
- Running-time: They established and strengthened seriousness though the long-term nature of the call by being not only a single action but continuously running over a long time
- Reachability: Austria has the advantage of having an over-regional, country-wide radio station that reaches up to 2.8 million people per day
- Content: the content of the topic (especially social and ecologic aspects) became part of the radio-program (“educated” the listeners)

German Telekom Company

The German Telekom Company has been spending an extensive amount of resources in investigating the relatively low amount of returned mobile phones for many years [30]. Recently, they also launched a marketing research investigated the knowledge base (need of separate disposal of mobile phones for preservation of resources) in German households. Here, we included two of their prominent take-back campaigns in our paper:

- Winning game (raffle for 5 cars), year 2010: collected 62.000 mobile phones in 3 months (total 2010 collected: approx. 200,000)
- Charity event (donation for children), year 2011: collected 585,700 mobile phones in 3 months (total 2011 collected: 762,000)

These are only two of recent German campaigns, but they seem to undermine the trend that we believe to see: the most effective activity has been the medial attentive and widely advertised activity in 2011 with a prominent German entertainer for a well-known children donation project.

From the second campaign, we can draw some similar conclusions as success factors compared to the activities in Austria. The second program included in our analysis was clearly marked as a charity event, even though coming from a large corporation; an aspect, which might raise some suspicions from people as this is often seen as marketing activity. However, it was made clear where the donations went (a quite well known charity organization in Germany). Furthermore, the corporation chose a set or media known of reaching quite a large part of the German population. Therefore the setting is close to the Austrian case, even though the campaign was embedded in a different country- specific situation.

In terms of educational measures supporting the campaign as seen in Austria, both activities in Germany did not really include such communication efforts. The content of the topic, such as environmental effects of mobile phone production, use and recycling, was presented to a limited extend; information about these issues was included but no deeper explanation of the whole picture of sustainability and mobile phones. This, however, would not have been the type of information and in-depth content suitable for the media chosen in both campaigns – thus, the content was quite fitting for the chosen communication channels.

Another aspect which was not discussed in the Austrian case but which we see as quite important in the German campaigns was the selection of take-back channels and possibilities for people interested in participating. Both German campaigns provided tools for returning the mobile phone as easy as possible, including special postal envelops, which could be returned free of charge and with as little effort as possible. In our research underlying this paper, we found some articles discussing this aspect as quite important for such campaigns to succeed.

7.5. Implications

Summarizing the results to promote recommendations for return- programs, we would like to stress that no single factor accounts for a successful program. Rather, a combination of proposed conditions appears to be the key.

Here, we give an overview of aspects that seem to have influenced the investigated worldwide programs, concentrating on the two further investigated programs in Austria and Germany, and referring the results to the UTAUT measures. An overview of all identified success factors can be seen in table 2 below, the most important ones being explained in the following paragraphs.

- **Performance expectancy**: Charity objectives seem to have a stronger impact than other intentions (raffle, price-winning for returned phones etc.); also, clear and visible goals are important. Still, programs offering money for returned phones also could have a noticeable influence but only account to newer mobile phones that can still be used and therefore rather support the category of re-use, which is not the topic of our investigation.
- **Effort expectancy**: minimum effort seems to be the key factor in this category, so that no cost or extra-ways arise and participating people can easily drop off or mail in their mobile phones. E.g. free envelopes sent to households showed a reasonable positive impact. Still, one of the German campaigns showed clearly that this factor is indeed important but not sufficient on its own for a successful campaign.
- **Facilitating Conditions**: Reliable and trustworthy partner: The fact that governmental or non-profit organizations and well-known NGO's were involved seemed to have a positive impact. In general, governmental supported actions seemed to run well, implicating that a legal and trustworthy factor might also be one of the key factors in these programs. It seems to influence people that reliable partner reduce the chance of misconduct of their mobile phones; trustworthy partner seemed to give a certainty that the mobile phones get treated correctly (e.g.in terms of possible deletion of private content as well as being sent to reliable recycling processes and not being sold to deceptive businesses, nor making money in any way with it). This way, the program does not have the character of a business or selling program but rather a trustworthy idea with a clear incentive.
- **Social Influence**: The image of the initiator and their partners seem to influence people's decision in returning their mobile phones. Therefore, an activity initiated by a large corporation might get a less positive reaction than one initiated by a local radio station, as included here in this paper (see facilitating conditions).

Performance Expectancy	Effort Expectancy	Social Influence	Facilitating Conditions
• **Donations to charity** • Vouchers or money for returned phone • Games/competitive character • Verifiable environmental protection measures (e.g. planting trees)	• **Minimizing the effort** in terms of time and costs for using a return program (e.g. free mail ins, return boxes at favorite and frequented locations, pick-up services) • Enabling easy ways to save and delete own data from mobile phones	• **Image of the initiator** • Raising awareness in groups (e.g. school competitions, social media networks) • Testimonials (e.g. people from politics, culture and sports)	• **Trust in the initiator** of the program by high levels of transparency • Providing information and knowledge on why, where, how, when (e.g. TV, radio, internet ads)

Table 7.2. *Measures Influencing the Return Program Acceptance Factors; in bold the seemingly most inductive factors*

7.6. Conclusion

By combing the UTAUT theory with the investigated case studies we can assign different measures to specific factors of technology acceptance (see Table 2). This provides decision makers with a structured overview of possible measure to successfully implement mobile phone return programs. Researchers can use the model, included in this paper and extended by the identified success factors, to evaluate return programs and to determine drivers and barriers of adoption. Depending on the context (country, target group, duration of the campaign, etc.) some of the identified factors here can take a more prominent role than others. This may change according to the different campaigns, therefore, there is no universal “check list” for setting up a successful mobile phone return program. Still, based on the results from this paper, we can recommend taking into account these findings and applying them according to the characteristics of the defined target group.

In order to refine the recommendations deducted from the model and its aligned success factors, needing more research, the model can be further developed and refined for explaining and understanding human behavior in terms of responding to such campaigns and changing their behavior accordingly. Such campaigns in this context of mobile phone recycling are just starting, thus, more empirical data is needed besides the theoretical background gathered for this paper.

Therefore, to refine the results from our research so far, our future research will follow these next steps:

- In depth case studies and continuing expert interviews
- Small and large scale surveys with users and non-users of mobile phone return programs

Given the rising prices for rare materials and the increasing awareness regarding environmental protection, the topic of mobile phone recycling is destined to gain more importance in the future. Hence, related concepts and measures have an increased relevance for policy makers, practitioners, and researchers. Here, again, it is important to design, implement and evaluate respective campaigns successfully in order to reach expected outcomes and behavioral changes and avoid wasting resources. This paper is a first tentative step towards such concept for both designing a successful campaign and evaluating it for further improvements in this context.

7.7. Authorship contribution

B. Bookhagen - Conceptualization, Methodology, Data curation, Interpretation, Writing - original draft.

J. Nordmann – Conceptualization.

I. Dyrnes - Writing - review & editing.

O. Stengel - Writing - review & editing.

NH Schmidt - Writing - review & editing; Supervision.

7.8. References

[1] AMTA (Australian Mobile Telecommunications Association) http://www.amta.org.au/pages/amta/Check.the.Status.of.your. Handset

[2] Arnfalk, P.; Erdmann, L.; Goodman, J.; Hilty, L. M. (2004). The future impact of ICT on environmental Sustainability. European Commission Technical Report EUR 21384 EN

[3] BITKOM (Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e.V.) http://www.bitkom.org/ retrieved Sep 2012

[4] Baron, R. M., & Kenny, D. A. (1986). The moderator- mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. Journal of Personality and Social Psychology, 51, 1173-1182.

[5] Benbasat I., Goldstein D. K., Mead M. (1987). The Case Research Strategy in Studies of Information Systems. In: MIS Quarterly, 11 (1987), pp. 369-386

[6] Cardoso, A. & Carvalho, J. (2011). Using green is to encourage recycling behavior. MCIS 2011 Proceedings. Available at: http://aisel.aisnet.org/mcis2011/23. Retrieved Sep 2012

[7] Davis, F. D., Bagozzi, R. P., and Warshaw, P. R. (1989). User Acceptance of Computer Technology: A Comparison of Two Theoretical Models. Management Science, 35, 982-1003.

[8] Dubé L, Paré G (2003). Rigor in Information Systems Positivist Case Research: Current Practices. MIS Quarterly 27(4). 597-635

[9] Eisenhardt, K.M. (1989). Building Theories from Case Study Research. The Academy of Management Review, 14(4), S.532–550.

[10] EPA (US Environmental Protection Agency). Plugin to cell phones. http://www.epa.gov/osw/partnerships/plugin/cellphone/ retrieved Sep 2012

[11] Eurostat (2008). Statistical office of the European Union http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/weee retrieved Sep 2012

[12] Folz, Hazlett (1991). Public Participation and Recycling Performance: Explaining Program Success. Public Administration Review, Vol. 51, No. 6, pp. 526-532

[13] Fonebak. UK Cell Phone recycling. http://www.fonebak.com/ retrieved Sep 2012

[14] Geyer, Blass (2010). The economics of cell phone reuse and recycling. International Journal of Advanced Manufacturing Technology. 47:515–525

[15] Hagelüken (2010). Wir brauchen ein globale Recyclingwirtschaft, exerts from a talk given in Vienna, retrieved Sep 2012 http://www.nachhaltigwirtschaften.at/nw_pdf/events/20101011_rohstoffversorgung_christian_hagelueken.pdf

[16] Hilty, Arnfalk, Erdmann, Goodman, Lehmann, Wäger (2006). The relevance of information and communication technologies for environmental sustainability – a prospective simulation study. Environmental Modelling & Software, 11, pp. 1618–1629

[17] Hornik, J., Cherian, J., Madansky, M. and Narayana, C. (1995). Determinants of Recycling Behavior: A Synthesis of Research Results. Journal of Socio-Economics, 24(1), 105-127

[18] Kim, Y, Zhang, P (2010). Continued Use of Technology: Combining Controlled and Automatic Processes; In: Proceedings of the 31st International Conference on Information Systems, St.Louis, paper 214.

[19] King, W.R. (2006). A meta-analysis of the technology acceptance model. Information & Management (43:6), pp. 740-755.

[20] McLaren J, Wright L, Parkinson S, Jackson T (1999). A dynamic life-cycle energy model of mobile phone take-back and recycling. Journal of Industrial Ecology 2(1):77–91

[21] Mobilemuster. Australian recycling program http://www.mobilemuster.com.au/ retrieved Sep, 2012

[22] Nabu. Naturschutzbund. http://www.nabu.de/themen/konsumressourcenmuell/waskannichtun/handyrecycling/index.html retrieved Sep 2012

[23] Nokia (2005). Integrated Product Policy Pilot Project: Life Cycle Environmental Issues of Mobile Phones. http://ec.europa.eu/environment/ipp/pdf/nokia_mobile_05_04.pdf retrieved Sep 2012

[24] Ö3 Radio. Austrian radio station. http://oe3.orf.at/aktionen/stories/542230/ and http://www.wundertuete-macht-schule.at/ retrieved Sep 2012

[25] OECD (2010). Materials Case Study 1: Critical Metals and Mobile Devices. Working Document by the OECD Environment Directorate,available at http://www.oecd.org/dataoecd/26/45/46132634.pdf retrieved Sep 2012

[26] Opitz, N., Langkau, T. F., Schmidt, N.-H., Kolbe,L. M. (2012). Technology Acceptance of Cloud Computing: Empirical Evidence from German IT Departments. Proceedings of the Hawaii International Conference on System Sciences (HICSS), Maui, Hawaii,2012

[27] Reller A, Bublies T, Staudinger T, Oswald I, Meißner S, Allen M (2009). The Mobile Phone: Powerful Communicator and Potential Metal Dissipator. GAIA - Ökologische Perspektiven für Wissenschaft und Gesellschaft"

[28] Tanskanen und Butler (2007). Mobile phone take back learning's from various initiatives. Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, pp.206-209

[29] Telekom. Deutsche Telekom Recycling http://www.t- mobile.de/handy-ruecknahme/0,22762,24795-_,00.html retrieved Sep 2012

[30] Telekom. Deutsche Telekom CR-report http://www.cr-bericht.telekom.com/site12/kennzahlen/oekologische- kennzahlen/handy-ruecknahme-abfallaufkommen , retrieved Sep 2012

[31] UNEP (2008). United Nations Environment Program and the Mobile Phone Partnership Initiative (MPPI): Guidance document on the environmentally sound management of used and end-of-life mobile phones. http://archive.basel.int/meetings/oewg/oewg7/docs/oewg07- inf07.pdf retrieved Sep, 2012

[32] USGS (2006). US Geological Survey: Fact Sheet Recycled cell phones http://pubs.usgs.gov/fs/2006/3097/ retrieved Sep 2012

[33] Venkatesh (2012). http://www.vvenkatesh.com/it/organizations/Theoretical_Models.asp

[34] Venkatesh V, Morris MG, Davis FD, Davis GB (2003). User Acceptance of Information Technology: Toward a Unified View. MIS Quarterly, 27, 425-478.

[35] Venkatesh V and Bala H (2004). TAM 3: Advancing the Technology Acceptance Model with a Focus on Interventions. Manuscript in-preparation

[36] Venkatesh, V. and Davis, F.D (2000). A Theoretical Extension of the Technology Acceptance Model: Four Longitudinal Field Studies," Management Science, 46, 186-204.

[37] Vining, Joanne and Angela Ebreo (1990). "What Makes a Recycler? A Comparison of Recyclers and Nonrecyclers."Environment and Bebavior, Vol. 22, pp. 55-73.

[38] Vodafone. Company data. http://www.vodafone.de/unternehmen/recycling/handy- recycling-engagement.html retrieved Sep 2012

[39] WEEE directive. European Commission. http://ec.europa.eu/environment/waste/weee/index_en.htm retrieved Sep 2012

[40] Widmer, Oswald-Krapf, Sinha-Khetriwalb, Schnellmann, Boeni (2005). Global perspectives on ewaste. Environmental Impact Assessment Review 25 (2005) 436–458

8. Mineral resources in mobile phones: A case study of Boston and Vienna teachers and students. Curriculum development for an interdisciplinary teaching tool in sustainability

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Published 2017 in **Journal of Geoscience Education (JGE): Special Issue Interdisciplinary Teaching and Sustainability.** 65 (2). Pages 113-125. https://doi.org/10.5408/16-151.1

First received 29 Feb 2016, accepted 06 Mar 2017

Key words: mineral resources in school curricula; interdisciplinary teaching; mobile phones; sustainability

Abstract

As part of an outreach initiative by the Natural History Museum in Vienna, an interdisciplinary educational module was developed to teach students about sustainability through the lens of mineral resources used to produce mobile phones. The overall goal of the module is to provide teachers of different subjects with a multi-faceted tool to include sustainability in their classrooms and create greater awareness of our resource-rich lifestyle. The evaluation of efficacy and impact of the module in formal classroom environments is facilitated through two case studies: an assessment of teacher experiences across Austria with our teaching kit, and an assessment of student learning in Austria and USA. During the development of the teaching module in Austria, workshops with 97 teachers were conducted to identify educators' needs and offer an interdisciplinary usable teaching kit. The study showed that teachers greatly appreciated the hands-on workshops and implemented the module in their curriculum. For the student study, 416 students from Vienna, Austria (209 students) and the Greater Boston Area, USA (207 students) were taught the same module by the same instructor. Student performance and learning impact were assessed using pre- and post-questionnaires. For the Austrian students, an additional long-term post-questionnaire was completed six months after the intervention. Students' short-term performances increased significantly immediately after the module.

This paper describes the outreach project and our teaching module, and proposes the development of curriculum extensions and teacher professional development for implementing interdisciplinary science concepts.

8.1. Purpose and learning goals

Ensuring environmental sustainability is one of the eight United Nations 2015 Millennium Development Goals (UNDP, 2000). To achieve this goal, all citizens require a fundamental understanding of science, technology, engineering and mathematics (STEM) to make environmentally sound decisions, and the STEM education community needs collaboration with competent scientists to develop a scientifically literate society as well as inspire future scientists (AAAS, 1993; NSF, 1996; NRC, 1997).

Today humanity faces many sustainability challenges ranging from declining mineral resources, air and land pollution, to water shortages and changing global climate - all directly related to the Earth sciences (Locke, Libarkin, & Chang, 2012). This especially includes knowledge about soils, water, air, and other resources that need to be handled sensitively – thus making Earth science literacy a key component to generate policies that appropriately weigh the importance of resource conservation, use, and sustainability (Feinstein & Kirchgasler, 2015). The Earth Science Literacy Initiative (ESLI, 2010), funded by the US National Science Foundation, developed a framework of underlying principles in Earth science, and identified “resources” as big idea number 7: “Humans depend on Earth for resources”.

However, young people tend to be unaware of their resource intensive lifestyle and many seem to feel that their lives are not connected to the environment (Michigan Teacher Expert Program, MiTEP, 2010). Project 2061, an initiative of the American Association for the Advancement of Science (AAAS) has identified several common geoscience misconceptions related to mineral resources as reported by the MiTEP (MiTEP, 2010):

- “Diamonds, gold, and silver are valuable, therefore, they are not rocks or minerals”
- "Manmade materials do not come from mineral resources.”
- “Earth's resources are not finite -- there is an endless supply of water, petroleum, and mineral resources. All we have to do is to explore for them.”

When focusing on electronic consumables such as mobile phones and notepads, it furthermore needs to be understood that virtually every good that we use originates from natural resources. Many of these origins are not directly visible and the misconceptions above suggest that students do not make connections between minerals, mining and the goods they buy. Therefore, we have developed a learning experience to address these misconceptions and used mobile phones as an exemplary device. Ultimately, students need to make the connection between their lives and our earth in order for them to understand that we are not detached from nature even if it is not visible, for instance, in consumables.

Understanding about resources and environmental protection is also an important concept in geology, combining knowledge about earth's interacting system processes and integrating elements of chemistry, physics, and biology. Understanding the topic of mineral resources also takes into account social, political and economic aspects of a globalized world through an increased awareness and understanding of mining, production and issues accompanied with these processes. Thus, teaching about resources in mobile phones provides a unique opportunity to introduce students to key scientific concepts that integrate knowledge from a diverse range of disciplines and have a meaningful connection to their current lifestyle. Although the topic can be broken down into many facts in a very broad interdisciplinary setting, in **Table 8.1** we only list the main geoscientific related learning goals.

Electrical and electronic equipment (EEE) make up a large amount of consumables: in the European Union in 2012, 9.1 million tons of EEE were put on the market. The second largest amount of these are ICT (information communication technology), after large household appliances (e.g., refrigerators, which are much heavier per single device (Eurostat, 2015). Used, end-of-life ICT devices make up a large quantity of W(aste)EEE, but the collection numbers are still not satisfying (Hagelüken, 2010) and stand at a 5-8% collection rate (Eurostat, 2015). For the USA, the numbers are similar, in 2011 only 11% of mobile phones were recycled and the rest was trashed (EPA, 2011).

In our module, we wanted to provide teachers with an overview of all the different topics related to mineral raw materials and their sustainable usage in all day life as an appreciation of resources ("geology is everywhere"). The topic can be used to cover many issues and thus comprises many learning goals in the social sciences (humangeography, ethics, and economics) and natural sciences (chemistry, physics, biology, ecology). Focusing on geoscientific and sustainability issues, some of the main foci are listed here as learning goals but can differ ac-cording to teachers' usage and needs.

ICT devices include netbooks, laptops, tablets, and mobile phones. We used mobile phones as representative for the vast amount of ICT-devices as they provide a useful example: 1.9 billion devices were sold worldwide in 2015 (Gartner, 2016). In Austria, 97% of youth older than 14 years possess their own mobile phone (Edugroup, 2015). As for the USA, surveys specifiying the youth population are out-dated (2012), although current numbers from adults with 95% (PewResearchCenter, 2017), combined with our own questions while teaching suggest a similar coverage. With a low recycling rate of 5-8% and a rapid turnover of every 18-24 months (Gartner, 2015) – many mobile phones are being replaced in spite of still being functional - the need for targeted education concerning this topic clear.

Learning Goals

1. Students are able to demonstrate their understanding that mobile phones contain many different materials, especially metals. They are able to name at least 7 different metals contained in a mobile phone.
2. Students are able to briefly explain that for producing metals, ores and rocks need to be mined. Students are able to identify that gold, silver and aluminum (to name a few) are all metals mined from ores/rocks.
3. Students are able to sketchily describe that plastics are derived from crude oil.
4. Students are able to briefly explain that natural resources are deprived from our Earth and are finite. Students are able to comprehend that we cannot just buy new resources once we have depleted them.
5. Students are able to analyze that for producing all our goods for now and for the future, we need to conserve these finite resources and treat them sustainably.
6. Students are able to apply critical thinking and explain why mining these materials can include ecologic, social and political issues. They are able to explain different example for each of the issues.
7. Students are able to exemplary explain why processes to make manufactural materials of these rocks and ores can be energy consuming and may include toxic chemicals. Consequently, students are able to demonstrate that using less resources saves energy and is ecologically responsible.
8. Students are able to explain why recycling is one way to help saving new resource from being mined. They can exemplary calculate or briefly explain that for most metals, recycling is less energy consuming than mining new metals from ores.
9. Students are able to demonstrate that using electrical devices as long as possible, reusing and repairing them if possible and having them professionally recycled once they are out of order is the most sustainable way of consuming electronics (share, borrow, lease and repair are some good ways of describing this).

Table 8.1: *Learning Goals*

A mobile phone consists of approximately 30% (weight) of different metals, 50% plastics, and 20% glass and ceramics, depending on the device and manufacturing year (UNEP, 2008). Mobile phones contain many valuable and rare metals (Hagelüken, 2010; OECD Environment Directorate, 2010; USGS, 2006). Due to the large quantity of mobile phones sold worldwide, even the comparably small constituency per single device adds up to a significant amount of highly valuable and non-renewable resources consumed in total. Furthermore, incorrect disposal of mobile phones can release toxic leftovers into the environment and pose potential health risks (Scharnhorst, et al., 2007; UNEP, 2008). Thus, mobile phones represent a device common to a modern lifestyle but due to aforementioned issues, cannot be related to an environmentally sustainable lifestyle (Bookhagen et al., 2013).

Understanding the significance of mineral resources as the basis of our society is clearly important, but it is also inherent for a sustainable lifestyle to inspire young people to move “from knowledge to action”, one of the goals of the federal education ministry in Austria (BMB, 2010). In the long-term, this means applying scientific content and problem-solving thinking to strive towards being a resource-sensible consumer. This can be correlated to levels 5 and 6 of Blooms’ categories in the cognitive domain (synthesis and evaluation) (Bloom, 1956). We hope that our module can give teachers a tool to help them introduce students to important facts and concepts that could potentially promote a resource-sensible mindset.

Literature context

The role of education in achieving a more sustainable lifestyle and the focus of environmental education has been described in the late twentieth century (Tilbury, 1995) and further expanded upon (Jones, 2010). The project InTeGrate (interdisciplinary teaching about Earth for a sustainable future), a National Science Foundation (NSF) STEP Center grant running from 2012-2016, conducted several workshops and summarized outcomes on their website (InTeGrate, 2016). Strategies included (i) connecting to the world we live in by using real world examples beyond the academic ivory tower, (ii) building interdisciplinary connections to integrate different viewpoints and (iii) connecting justice to sustainability by giving an ethical perspective of how sustainability issues affect people in different ways. Sustainability requires systems thinking, synthesis, and contributions from all disciplines—geoscientists, natural/ physical scientists, social scientists and engineers (Gosselin, 2013). However, a study of preservice teachers indicated their knowledge base regarding environmental issues was minimal and insight into the social, cultural and economic complexities was quite superficial (Stir, 2006). Our teachers’ feedback from a previous study (Bookhagen, 2014) also indicated that modules implementing geosciences in interdisciplinary teaching were appreciated as teachers often do not find the time to prepare these lessons or do not feel comfortable enough in making these connections on their own.

In a previous study (Bookhagen et al., 2013), we investigated people’s acceptance of mobile phone return programs and concluded that many people lack information about where to return the mobile phones and why there is a need for proper returning/recycling. Being unaware of the many and valuable resources in a mobile phone was one barrier, mainly because people do not see the need and will therefore not make the effort necessary to recycle these devices. Also, people were unaware of the social aspects connected to mining some of the metals and that social and ecological conditions in the mining sector can be complicated. Our inquiry indicated that educational materials, implementing a sustainability approach, were needed which emphasize both social aspects as well as the scientific background. We felt that a special focus on the geosciences would be ideal to integrate these aspects. Information material that we collected for our module did not provide enough background information and only implemented either the social or science aspects but not both (USGS 2006; SWICO, 2009)).

We developed a module that combines the mentioned strategies and aspects using inquiry based-teaching and hands-on activities. Also, we adhered to the conceptual framework of the three dimensions suggested by the NGSS guidelines by following the suggested major practices, crosscutting concepts, and disciplinary core ideas (NGSS, 2013). Our topic specifically covers NGSS' Earth and Space Sciences (ESS) third core idea, Earth and Human Activity, explicitly ESS3.A: Natural Resources and ESS3.C: Human Impacts on Earth Systems) and ESS2: Earth's System ESS2.A: Earth Materials and Systems which should also be covered for general understanding (see also NRC, 2012).

Following Piaget's constructivist learning theory (Piaget, 1967) which states that learners construct knowledge for themselves, students should be encouraged to learn more than just facts and theories in order to effectively understand science (NRC, 1997; NCES, 2013). With inquiry-based teaching and hands-on activities, where students formulate and test their own ideas, teachers can help students to gather understanding and knowledge rather than reproducing a series of facts. Constructivism transforms the student from a passive recipient of information to an active participant in the learning process. Both methods have also been shown to facilitate learning complex topics (e.g., Barab & Luehmann, 2003; Breslyn & McGinnis, 2012) which supports our multifaceted topic (InTeGrate, 2016). UNESCO also encourages teaching and learning for a sustainable future by using inquiry-based teaching, where students carry out some sort of investigation rather than solely being lectured by the teacher (UNESCO, 2010). Creating understanding through an iterative process which seizes and reforms prior knowledge (National Research Council, 1997) and includes relevant current issues has also been shown to be supportive for the learning process (Ballantyne et al., 2001). We encouraged students to become engaged by applying their existing knowledge and real-world experience with a device they care for and feel connected to. We asked students to hypothesize and test their theories to draw conclusions from their own findings, thus forming their own opinion by using all the facts they gathered.

Teachers who enjoy and are passionate about a topic are more likely to present the lesson in a more engaging and effective way to their students (Hattie, 2003). Subsequently, we focused on a relevant and interesting topic for the teacher as well as the student. As summarized by Breslyn (2011), a lack of planning and instructional time, insufficient materials, and inadequate professional development have frequently been cited in the research literature as barriers to inquiry-based teaching and the implementation of hands-on modules for teachers. Findings from our previous study with teachers (Bookhagen et al., 2014) suggested that ready-to-use lesson plans with hands-on tools in Earth sciences would be greatly appreciated and could be another way to strengthen the application of Earth sciences and encourage teaching in school. Thus, we developed this mobile phone module as an educational outreach activity. We also included a brief teacher study in our outreach project, as research on teachers has also been coming into focus (e.g., Remillard, 2009).

Study population and setting

The International Council of Museums (ICOM) states the significance of museums as follows: "Museums have an important duty to develop their educational role and attract wider audiences from the community."(ICOM Principle no 4). Especially for Earth Sciences, museums and their school programs play an important role (Ramey-Gassert, Walberg, & Walberg, 1994; Hooper-Greenhill, 2007). The Natural History Museum in Vienna (NHM) plays a leading role in the country's geoscientific educational outreach activities in out-of-school learning places. In 2014 it had approximately 2300 classes using the available activities specifically designed for schools.

Approximately 50,000 students visit the NHM every year (average from 2011-2014) and hear about a wide range of science topics, ranging from paleontology, archaeology and biology to geology. The NHM museum pedagogy has a long history of developing educational modules with exercises and teaching material that provide students with multiple opportunities to explore difficult concepts in natural science and Earth science. Usually, these modules take place at the museum as part of a class visit. However, not all teachers can bring their classes to the museum. Teachers and schools that are unable to visit the museum (due to distance, time or funding) should have access to similar learning experiences without the displayed exhibitions. Ready-to-use modules which can be obtained as kits is an important method of expanding accessibility of these topics and learning experiences. Our module development began as an educational outreach part of the museum and continues to be part of the museum work. The module testing in a formal classroom environment was facilitated through two case studies: an assessment of teacher experiences across Austria (**Study 1**), and an assessment of student learning in Austria and Boston, USA (**Study 2**).

The teacher study illustrates the usage of this cross-disciplinary topic and pre-made material kits in the classroom. The student study shows the possible topics and the need for emphasis which teachers can choose to focus on, depending on their learning goals, in regards to teaching about sustainability and natural resources.

Study 1: Teachers in Austria

Teachers were recruited via an email distribution list from the museum that reaches federal school authorities and schools throughout Austria. In the free three-hour teacher workshops we introduced the prototype-material box in November/ December 2011, each teacher could keep a classroom set of the material box (four boxes) free of charge. Teacher questionnaires were distributed via email ten months after the teacher workshops to measure teacher's feedback of the module and their implementation in the classroom.

We conducted ten professional development teacher workshops across Austria at local schools in each federal district. All 97 teachers came from different public schools. Experience from teachers varied from beginners to proficient and they came from a wide range of backgrounds, including chemistry, biology, physics, geography, political science and social science as well a religious education (a partly facultative school subject in Austria) and technical subjects. Instructors were teaching grade 7 and up with students aged 13 and older. Eight teachers also worked in grade 5. Of the teachers, 44 teachers were male and 53 female.

Study 2: Students in the USA and Austria

For our student study and material kit assessment, the same teacher taught the same module to students in the USA (May 2012, N=207) and Austria (June/July 2012, N=269). All schools for the study were recommended by teachers from a previous study, so we did not know the teachers or students beforehand. All parts of the module were translated from German to English (worksheets, PowerPoint presentation, quiz game). Time controls were only slightly modified when necessary to fit practical needs, such as having 90 minutes vs 80 minutes, and two single lectures vs double block lectures (3 out of 10 classes).

Parents submitted a signed consent form granting permission for their child(ren) to participate in the study, and students signed assent forms acknowledging their participation. Students were made aware that they would not be graded, that the survey would be solely for assessment of our teaching methods and would be treated confidentially. Students were given sufficient time to complete the questionnaires, which took an average of seven minutes.

Students from both countries were from the same age group. In Vienna, altogether 269 students from three schools participated; 209 students were from grades 9, 10, and 11. We also included two classes from grade 7 and 8 (60 students) to test and compare whether the material and subject would be appropriate with younger students. In Boston, 207 students from three schools participated from Grades 9, 10, and 11. In the Vienna sample, 57% of the students were female and 43% were male.

In the Boston sample, 49% of students were female and 51% were male. All schools in Vienna and Boston were public schools. School type and social standing of test schools were comparable. All settings were chosen to be comparable (time, age group, class size, gender distribution and social standing).

8.2. Materials and implementation

In this section we provide an overview of the module development and kit content as a model for instructors or organizations interested in conceptualizing and developing their own interdisciplinary teaching kits. We also describe an exemplary 90-minute-

Representative Material	Where in mobile phone	Topic addressed/reason for inclusion
Iron (ore: magnetite)	Little screws and bolts	Great for showing a magnetic rock; iron well known metal, abundant, high connection to industrialization and mining history
Copper (ore: chalcopyrite)	Cables and connectors, sheeted in printed circuit board, etc.	Abundant; very important metal; diversity of usage and recycling of copper
Gold (gold foil)	Corrosion resistant contacts and thin bondwires	Well known and extravagant metal; high environmental impact when mined; ecological and social aspects of small-scale mining; recycling
Aluminum (ore: bauxite)	Thin covers/plates on printed circuit board	Well known metal; high environmental impact for processing; good example for energy-saving when recycled
Silicon (mineral: quartz; and polysilicon, early stage of processing)	Microchips and processors (key component for ICs); also glass for display	Abundant mineral; diverse application for plain glass as well as high-tech Silicon-wafers for microchips
Lithium (ore: lepidolite)	Battery	Important element for future technologies (Li-ion batteries); beautiful mineral; concentrated only in few countries (scarcity)
Tantalum (ore “coltan”)	Electronic capacitors and multichip resistor arrays	Tiny amount needed but very important; has been connected to child labor and named as conflict mineral (social conflicts, war in DR Congo; Dodd Franc Act etc.)
Oil shale and plastic pellets (early processing state)	plastics (polymers) in case and as covers, isolators	Importance of crude oil (not suitable for classroom due to safety and health reasons) as a base for so many applications other than as fuel for cars (e.g., chemicals for medicine, soaps, detergents)
Clay minerals	Isolators, in multilayered capacitors	Seemingly unimpressive yet common in daily life and used in highly sophisticated applications (from coffee mug to cosmetics to special ceramics)

***Table 8.2**: Materials used in the box to address different topics and their location in a mobile phone*

Listed here are the ores which we used for our material box, their application in mobile phones and the reason for choosing these materials.

part of the module and provide supplemental teaching material. We then evaluate the efficiency of the module and material kit as curriculum supplements in formal classroom environments.

The teaching kit was developed through an iterative, collaborative process, first involving pilot tests with test students, followed by teacher workshops, during which the lessons were continually revised, as recommended by Briggs et al. (1991). The evaluation of the module was facilitated by examining teacher feedback after teachers from these workshops taught the module themselves (N=97), as well as by assessing student learning in Austria and the USA with test classes (N=416 in grades 9, 10, 11 and 60 in grades 7, 8) that were taught by us. The first author is a scientist working in the field of materials in mobile phones but has also been working with teachers and students for over ten years.

Over six months during the development of the accompanying kit and lesson plans in spring/summer 2011, we pilot tested the module with students. This included four sample classes with a total of 83 students from the targeted age group (grades 9 and 10). These test lessons with students provided valuable feedback to refine the material box and test hands-on exercises in order to produce a prototype. The following teacher workshops in November/December 2011 with this prototype teaching-kit and preliminary worksheets were conducted with 97 teachers all over Austria, and direct written and oral feedback was collected. The teacher workshops were designed to give in-depth information and ideas of how broad and interdisciplinary the subject could be taught as well as coaching the hands-on exercises that could be done with the students in the classroom. After the teacher workshops, the module was adapted to fit teachers' needs. A teacher background workbook was developed with further information, ready-to-use worksheets and solutions, and suggestions for possible instruction methods that were developed iteratively during the workshops together with the teachers. Teachers also received the presentation used for the workshops. The teacher workbook and presentation were mailed to teachers approximately two months after the workshops were conducted (January 2012). Please note that all "worksheets" were in MS Word-format so teachers could adapt them to their own needs and were to be used as starting point for students' discussions. The workbook is comprised of 101 pages (including worksheets), thus we only included a few focus topics in this paper. Each teacher received the complete package consisting of the material box, presentation and workbook.

The final material box for conducting the student test classes in Austria and the USA remained the same as the prototype version except for slight modifications to the layout.

The material box contains eleven mineral raw materials used as representative mineral resources to manufacture mobile phones. Eight of these were untreated minerals/rocks and ores, and three were already processed (early stage of production). For classroom security reasons, we used oil shale instead of pure crude oil and refrained from using lithium salts and used a lithium ore instead. Teachers were asked to always make sure that students keep safety standards in mind: although none of the mentioned raw materials are toxic, students should not eat or lick minerals and always wash their hands after the exercise.

The module describes different phases of the life cycle of a mobile phone with hands-on exercises and discussions linking to mining, production, usage and the recycling phase. The minerals/rocks in the box were specifically chosen to address different topics in order to also include the social and ecological issues of the life cycle stages (e.g., conflict minerals, child labor, environmental pollutions in the vicinity of mines, etc.) as well as the need for conservation and protection of resources and their recycling.

Please see **Table 8.2** for the minerals/ores we chose, where they can be found in a mobile phone, and the reason for including the material with the accompanying topic. Teachers who would like to follow our module can use this table as an answer sheet, or use it to develop their own worksheets for students.

The instructions and safety standard measurements in supplement 1a should be reviewed before starting with the module. The 90-minute-module started with a practical exercise: In small groups (3-5 students), students disassembled a dysfunctional mobile phone and explored the different parts/components by naming them and discussing possible material content (using a prepared table, asking for the parts and material of the mobile phone, see supplement 1b). Depending on knowledge status, online research can already be integrated at this stage, but students were explicitly asked to explore. After discussing students' first thoughts of what they hypothesized to be the material of a mobile phone, they were asked where the materials and metals they named originate from in which students were guided to the terms ore, commodity and mineral raw material. In the next step, students were given the mineral resources box (**Figure 1**) to discover some representative mineral resources used

Figure 8.1: *Material box*

Picture of the mineral resources box in use; in the back, students use the board game to determine the names of the mineral resources to manufacture mobile phones. A magnifying glass and magnet are also included in the box to investigate minerals and smaller parts of the mobile phone. The accompanying quiz (see **supplement 1c**) for the box is a board game to help students name the mineral resources by physical properties. Students began by placing all minerals on the left side of the game and then continuously followed each question on the top to reach the stage where all minerals lie on the right hand side next to their name. After identifying all minerals with the quiz, which takes about 5-10 minutes, laminated cards were used (see **supplement 1d**, which is a list of the minerals resources represented in the box, cut into light grey and dark grey cards). We allowed students to use one smartphone per group to support their investigation via online search tools but this can also be done with computers/tablets. First, students sorted the metals (light grey cards, e.g., copper) to the matching mineral (e.g., chalcopyrite) and placed them next to the mineral on the board game. The next step was arranging the dark grey cards (list of the components of a mobile phone cut into cards) to the corresponding mineral/raw material. To conclude, students should find the matching component of the disassembled mobile phone and placed it next to the series. Thus, each mineral was matched with one light and one dark grey card and the connection from mineral resource to metal/commodity and mobile phone component was established. The exercise can also be accompanied by handing out a periodic table of the elements and having students mark all elements they hypothesize to be part of a mobile phone. See supplement 2 for the list of elements that can be part of a mobile phone.

Further exercises for main production countries and social and ecological issues of each commodity are another central point that can be included now or in the following lessons (the workbook provides premade worksheets for online research, group-work and station learning with students' presentations). Due to time restrictions, in our case study with students we discussed the topics of each commodity via a presentation where we provided much of this information. Students discussed how many mobile phones they have at home, where they should bring them when they are not needed anymore and why correct recycling is the most sustainable way of treating broken mobile phones.

The box and the ready-to-use lesson plan for teachers with teaching methods have been available at the Natural History Museum in Vienna for purchase. Also, since the teacher workshops are not available anymore, teachers could choose to organize a class trip and do the module in the museum. This is taught by our trained staff. In Austria, 2100 boxes were ordered between 2011 and 2015. The material kit also became part of the "Raw Materials Expedition" by the German Ministry of Education and Research (BMBF) in the Year of Science 2012, and 2000 boxes were sent out to schools, museums and other educational institutes throughout Germany. Both projects are now finished, and so far, no further funding has been acquired to produce new boxes.

8.3. Evaluation

Overall design and strategy

The teacher feedback study (study 1) investigated the practicability and functionality of the created module and the material kit in a classroom environment as well as the usage of different accompanying material (pre-made worksheets, ready-to-use presentation). We also wanted to explore whether there was need for teacher development workshops for using the material kits.

Student learning (study 2) was reflected to examine our module for effectiveness. We also wanted to compare students' pre-knowledge and perception of the subject in the USA and Austria to gain a first impression whether these differ significantly. All findings were used to further adapt the module for classroom usage and not for addressing a formal research question.

Methods

We utilized mostly quantitative datasets for the evaluation of both studies. For systematic comparison of large numbers, quantitative research is a reliable method (Punch, 2005; Creswell, 2002). Here, we merely wanted to test students' knowledge

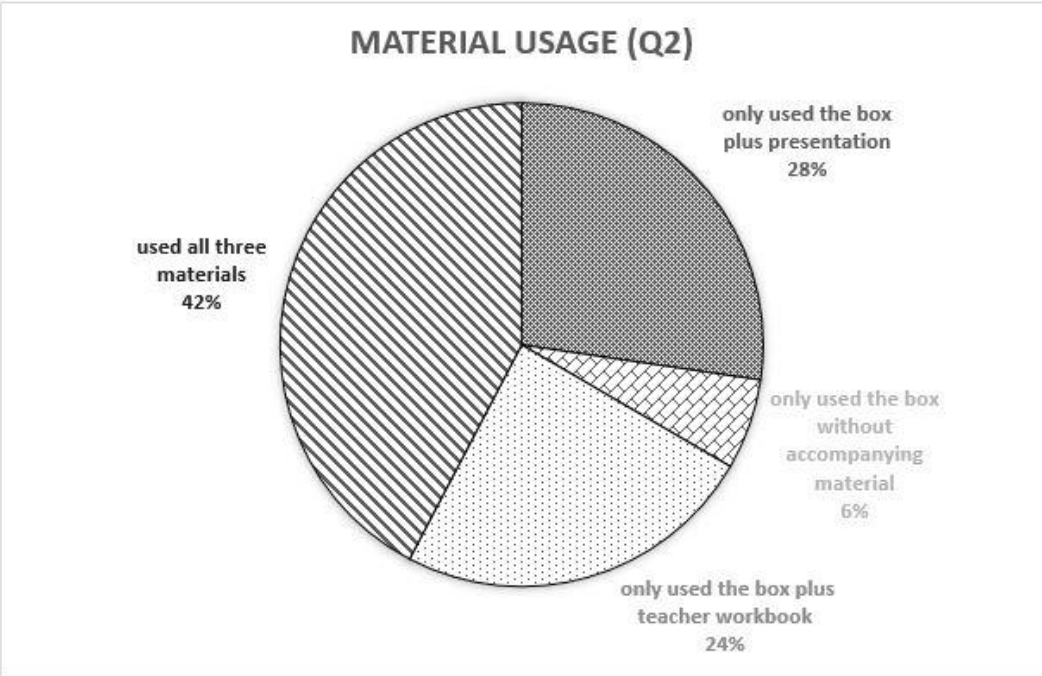


Figure 8.2: *Usage of the provided material types*

Teacher feedback (n=34) to question 2 (information about materials usage) from teachers who participated in the professional development workshops in Austria

gain and compare the results. We also included qualitative questions for a deeper understanding of contexts (Punch, 2005); since the topic covers a large range of aspects, we wanted to inspect which issues involved students the most. The qualitative answers from the questionnaires are only briefly summarized below. Please see supplement 3a for teacher questionnaires and supplement 3b for student's questionnaires. We used both datasets to obtain different. Of the 97 participating teachers from the workshops, 34 teachers returned their feedback questionnaire (37%) via email ten months after the teacher workshop. The chance of anonymous reply via post mail was also given. Teacher feedback was transferred into an excel-worksheet. All questions were Yes/No questions and coded accordingly (Yes=1, No=0). Additional qualitative explanations to the answers were collected.

The student surveys were administered at three stages: (1) immediately prior to science kit instruction (pre-test, N=476), (2) immediately after science kit instruction (post-test 1, N=476), and (3) approximately 6 months after science kit instruction (post-test 2, Austria only, N=200). Due to practical reasons, post-test 2 (long-term post-test) was only feasible for participating students from Austria. The long-term post-test from two test classes, then grade 7 and 8 in Austria, could not be obtained and were omitted from further consideration.

Pre-test and post-test 1 were printed on the same sheet (front and back side) to ensure paired testing.

In order to preserve anonymity, the Austrian long-term post-tests were not arranged to corresponding students but had to be analyzed blindly. Ten students were missing from classes. At each stage, the identical survey was administered. The long-term post-test for Austria had two additional qualitative questions. We calculated scores for Vienna students from 9th, 10th, and 11th (N=209) grade versus 7th and 8th (N=60) separately to better compare with the 9th, 10th, and 11th grade Boston students (N=207). Student questionnaires were transferred into an excel-worksheet. Open ended responses/qualitative data were sorted by similar thematic answer (questions 4-9) and used as information for how students understood the topic.

For student question 1 (which raw materials can be found in a mobile phone) multiple answers were possible. Incorrect answers include uranium, coal, radioactive rays and no answer at all. If students listed one incorrect answer even with a correct answer, we counted the entire question as incorrect. For correct answers, almost all metals from the periodic table can be accounted for in a mobile phone (see supplement 2). Since we stated the question purposely as “raw materials”, oil (to produce plastics) and broad terms such as metals were also allowed and counted as correct. For Questions 1 – 3, responses were coded as 0 = incorrect, 1 = correct.

Paired t-tests were used to compare two population means that are correlated (pre- and post-test of the same person) (Creswell, 2002). We determined the p value, which indicates the probability of the mean difference occurring by chance. We also calculated the effect size using Cohen’s d, which is the magnitude of the difference between groups (Cohen, 1990; Coe, 2002; Sullivan & Feinn, 2012). Statistics for p-values were calculated using GraphPad, an online statistics tool.

8.4. Results

Study 1

Almost all responding teachers (91%) stated the material was relevant for their curricula. Comments included the relevance and actuality of the topic, the interdisciplinary teaching opportunity, and that the whole package (material box, presentation and workbook with pre-made worksheets) fitted together well for individual classroom use.

Figure 8.2 shows the usage and different ways of using the material. Most teachers used all the provided materials (box, teacher workbook and ready-to-use presentation).

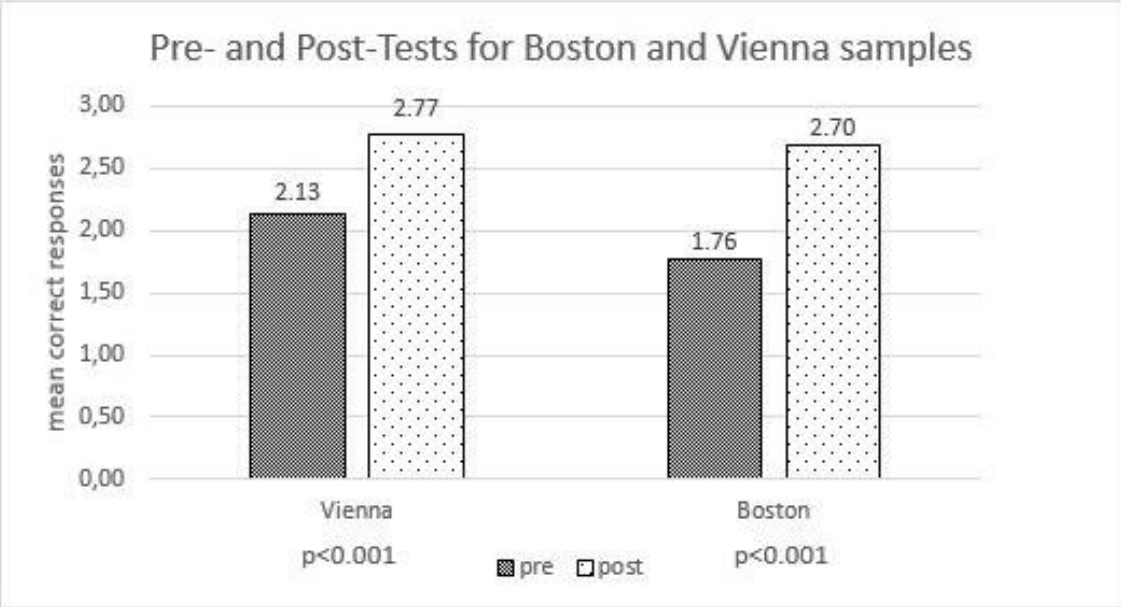


***Figure 8.2**: Average of pre- and post-test sum scores from Vienna and Boston*

Students' performance shows a significant increase from pre-test to post-test for both Vienna and Boston with p below 0.001, and a very large effect size with Cohen's d above 0.8

Table 8.3 summarizes information regarding school subject, class level/grade and thematic implementation of the material.

All respondents stated that disassembling a mobile phone alone would not have been sufficient and that the material box is a useful haptic tool. Comments included that actually holding raw materials - rocks - in their hand amazed most students and, according to teachers, helped in making the connection between origin and application.

Teachers perceived the teacher workshop as helpful, stating it efficiently showed the direct usage of the material and gave background information about the interdisciplinary topics that could be covered. Some stated it worked very well by getting them interested in the topic and prompted them to further explore the topic.

Twenty teachers would have used the material without the workshop, with 11 of them saying "yes, but… … not as confident/ not without a lot of preparation/ not knowing when they would have made the time to do so. Thirteen teachers stated they would not have/ probably not have used it due to time restraints for preparation, and four

School subject	in %
chemistry	53%
biology/ environmental sciences	50%
physics	32%
geography	18%
other	9%

Class level	in %
8. grade	56%
9. grade	47%
7. grade	38%
10. grade	38%
11. grade	15%
6. grade	12%
5.grade	9%
12. grade	6%

Topics addressed	in %
Recycling and recovery	71%
mineral resources and commodities	65%
ecological and social issues related to mining	35%
chemistry of the elements	32%
scarcity of resources	18%
geology	15%
rare earth metals	15%
Class project	12%
ecology	9%
mineral resources of Austria	6%
semiconductor technology	3%

***Table 8.3**: Implementation of the module by teachers*

Austrian teacher feedback (n=34) to question 3 (information about implementation of the module). Multiple answers were possible.

said they would not have used it at all. Eleven teachers specified that the workshop provided opportunities to question scientists knowledgeable about the subject and that the workshop inspired many ideas and possibilities about how to use the material interdisciplinary, which a mere self-study on the topic probably would not have covered.

Study 2

All teachers of the students' classes reported that they had not covered the topic prior to our intervention. Thus, we believe that students started on the same comparable level and the pre-test can be used as a starting

point to compare knowledge gain from our intervention (I-TECH, 2008). To strengthen this, we also assessed results of the two test classes from grade 7 and 8 in Austria (N=60) which mainly showed the same results in knowledge gain and were merely used to test whether the module can be used for younger students. These test results are not specifically included in this paper.

Supplement 4 shows the results of the 10 most named terms in question 1. Supplement 5 summarizes the correct answers for Vienna and Boston for all three questions 1-3 and test phases. Question 3 (What is plastic made up of?) was the question most answered incorrectly in both countries in the pre-test.

Figure 8.2 shows the average of pre- and post-test sum scores for the three quantitative questions. From an achievable sum score of 3 (scoring all of the three questions correctly), students in Vienna scored 2.13 on average in the pre-test and increased to 2.77 at post-test. Boston students started with an average score of 1.76 and increased to 2.7 at post-test. Using a paired t-test, students' performance shows a significant increase from pre-test to post-test for both areas with p below 0.001, and with a Cohen's d above 0.8, showing a very large effect size (Sullivan & Feinn, 2012). The paired sample t-test results for Vienna is t (203) = -12.00, p< .001, Cohen's d = -0.98 and for Boston is t (202) = -15.83, p< .001, Cohen's d = -1.29.

Generally, students in Vienna performed slightly better before instruction than students from Boston. Students' performance in Boston was still a little below Austria in the post-test after the instruction.

8.4.1. *Long-term Post-test (Austrian students only*)

All three test phases of Viennese students are summarized as a graph by mean correct answers in **Error! Reference source not found.**. Vienna students started with an verage of 2.13 correct answers in the pre-test and rose to 2.77 in the post-tests (paired t testing possible due to matched pre- and post-tests, (p<0.001). 6 months later, the same students' answers dropped to a 2.67 average. Overall, the knowledge gain from pre- to long-term post-test is statistically significant (independent t test, t(200)=-8.05, p<0.001, no paired t testing was possible due to anonymity). The knowledge loss from post-test to long-term post-test is not significant (t (200)=2.09, p=0.034). The effect size (Cohen's d) for Vienna pre-test and long-term post-test shows a large effect with -0.81. The effect size for Vienna post-test and long-term post-test is 0.21 which is a small effect. Altogether, the knowledge gain from pre- to long-term post-test is clearly visible and shows a large effect size.

Qualitative segments (questions 4-9 for students and feedback sections for teachers and students)

Students' answers for why mobile phones should be recycled showed all aspects in different foci: USA students mostly pointed to reusing resources (49%), taking care of toxic contents (31%), preserving the environment (20%) and saving valuable metals (20%). Austrian students mainly named reusing resources (35%), toxicity (24%) and saving resources (22%). When asked why they should not leave a mobile phone unused in a drawer, the most frequent response from both USA and Austrian students was some form of the "reuse and preservation of resources". USA students more often mentioned that some elements were valuable (53%), while more Austrian students stated preserving the environment (48%). In all qualitative post-test questionnaires, when asked what they liked most about the module, most (USA 87%; Austria 81%)

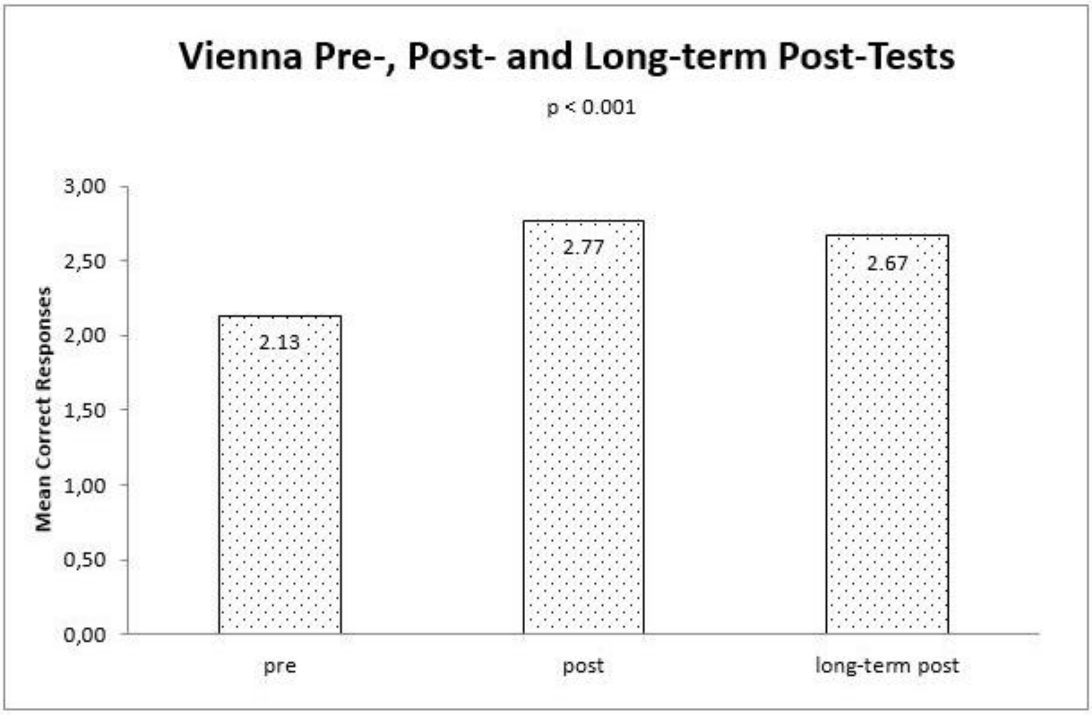


Figure 8.4*: Vienna students test scores for all test phases summarized by mean correct answer*

The knowledge gain from pre- to long-term post-test is statistically significant with p<0.001 and shows a large effect size.

answered disassembling the mobile phones, and handling the rocks/minerals (USA: 41%, Austria 36%). Students were able to state as many points as they liked.

Teachers

The interdisciplinary nature of the learning experience was specifically noted. The Austrian teachers stated that they are encouraged to teach interdisciplinary but that there are inadequate training opportunities to support such teaching. Teachers described that the provided material was relevant across several science disciplines, supporting the flexibility and applicability of the learning experience. Teachers stated that they and colleagues often avoided teaching mineralogy for lack of education and confidence but now felt more confident in teaching this module after completing the teacher workshop. Providing them with extensive background information to see the big picture was also praised. Teachers appreciated that they were thus able to choose their own key points suitable for such a complex topic and better fit it into their curricula. Some teachers stated they had never thought the subject “mobile phones” to be this extensive. One teacher stated “This topic is a bottomless pit and is great for further class projects”.

The room for comments was also used to thank us for the workshop and the prepared material, with seven teachers specifically stating they would like to have more prepared materials like this. In the oral feedback during instructions, teachers mentioned that they never thought the simple topic of mobile phones could lead to so many different aspects and insight in different learning subjects and topics. Nine teachers stated that they liked discussing the topic with other teachers which also engaged them in thinking about curriculum collaboration with colleagues from their school in order to implement the topic in different subjects.

Last but not least, in almost every workshop teachers noted that they themselves learned a lot about this complex topic and how many concerns are involved when talking about mobile phones. As one teacher stated: "Somehow we all know this but we never really think of it and never really implemented it in school."

Students

Notable students' quotes included: "cool doing something new and different", "didn't know rocks could be so cool". The need for recycling and preserving our resources was one of the solutions named to minimize our effects on natural resources, but in the discussion students also recognized that our consumer lifestyle does have an impact on our Earth. Many students were specifically upset by child labor and health issues connected to mining. Almost a third 32 % (USA) stated the notion that they didn't know things were so unfair. Students stated they were surprised that geoscience was connected to such a broad range of topics.

8.5. Interpretation

Teacher Experience

Our approach was appreciated by geography, chemistry and physics teachers as a good method to combine interdisciplinary subjects and bring a sustainability issue into the classroom through a hands-on approach and up-to-date topic that interested many students due to their daily affection with mobile phones - aspects which are also suggested by the InTeGrate findings (InTeGrate, 2016). Choosing a geoscientific content that can be clearly connected with other subjects proved to be another advantage to interdisciplinary teaching about sustainability as Gosselin (2013) suggests.

The teacher workshop assessment strongly supports Foley's (2013) observations: Teachers were mainly "looking for versatile curriculum supplements, not replacement curricula. They wanted hands-on lessons that related to ''hot'' topics that could be incorporated into their existing curriculum and aligned with state standards. They were virtually unanimous in not wanting a prescribed curriculum targeted at a specific grade or subject." Since sustainability teaching is mentioned in curricula of different subjects (BMUB, 2009), our approach is one useful way of connecting teachers of different backgrounds at schools, engaging them in an interdisciplinary topic, and attracting students to the topic as well (Hattie, 2003). However, since science standards in the USA and Austria are very different, we could only align them to Austrian standards when developing the module. Teachers from the USA, however, noted that the material would very well fit into their curricula and we have already noted their alignment to NGSS core ideas.

Students' Performance

Assessment of the module by measuring students' performance and by comparing the different countries shows that we have chosen a promising teaching method and topic. The noted actuality of the topic, all-day-related relevance and hands-on exercises in our methods support other projects' findings (InteGrate 2016).

Both Boston and Vienna samples show a significant increase in performance from pre- to post-test, suggesting the improvement can be attributed to our module. The scores of the pre-test results for questions 1-3 were already relatively high which may be due to the straightforwardness of the questions. We were also particularly interested in how students' answers would change from pre- to post-test in terms of naming different materials that can be attributed to our intervention (i.e., some of the materials that were not included in students' answers beforehand but showed up in the post-tests and thus can clearly be attributed to our intervention, see supplement 4). We also wanted to address misconceptions about radiation or rays (that some students attributed to radioactive materials such as uranium) to briefly mention the physical nature of electromagnetic waves. This issue has been a media-discussed topic for possible harmful rays in mobile phones and we wanted to highlight the science behind the issue.

We noticed that younger students (in grades 7 and 8) had problems using the cards and placing them next to the mineral resources, even when using online research. More confident pre-knowledge (e.g., in chemistry) seems to be needed to complete this task.

In general, we did not want to only teach about content but aimed at creating awareness of the complex topic of limited earth resources in connection with our consumer lifestyle and get students more curious about geoscientific contents. A quantitative and qualitative questionnaire will not be able to measure this impact. In-depth student interviews would clearly be more suitable to measure such an impact. However, this was not feasible for our study due to time restrictions, group size and location logistics in two countries.

Long term retention

The long-term post-test (Vienna only) shows that students seem to retain some of the knowledge (e.g., some materials contained in cell phones that were not mentioned before, such as silicon). However, it became apparent that they mostly remembered the part where they actively disassembled the mobile phones. The transfer of knowledge to a deeper understanding of the subject which we wanted to evaluate by using the term “sustainability” is difficult to measure. The long-term post-test from Vienna suggests that a single teaching module does not lead to a change in long sustained preconceptions for students (e.g., two students still answered “We can just buy all the raw materials we need”, which is the direct opposite of the intended message that our resources are limited). This suggests that other strategies need to be considered to improve a deeper retention. The content needs to be taught in different ways and repeatedly discussed to achieve a long term understanding as recommended by the NGSS 2013. The issue of consumer lifestyle affecting our earth does not usually come up in the everyday life of teenage students. Thus, although we started an important discussion with an innovative approach by using an everyday device such as a mobile phone, the topic needs to be addressed further in school as well as public discussions to lead to a deeper understanding.

8.6. Study limitations

Although even lower return rates than our achieved 37% of the teacher questionnaires are fairly typical with optional evaluations (Watt et al., 2002), we note that they can skew results, either toward high or low satisfaction. We suggest that the extremely positive results might be skewed due to highly motivated teachers who liked and used the material and who may have been more likely to return the questionnaires. Also, recruitment can always be a limitation due to reaching out to established mail servers. We cannot explain the relatively low response rate, although teachers were made aware of the follow-up during the workshops. We believe that it would have been beneficial to call teachers or write a second email to remind for missing responses, as Nulty (2008) proposes, to implicate a commitment. Watt et al. (2002) states that when paper surveys are not administered face to face, the response rates might be as low as for non-face-to-face online surveys. Still, considering liberal conditions that ask for at least 20% by more than 100 participants (Nulty, 2008), we believe that our response rates do show a representation of our methods and materials.

We cannot guarantee the fidelity of implementation through teachers since we were not able to test whether or not teachers implemented the lessons in a manner that was representative of our intent. But when looking at the subjects teachers chose (reported in question 3), we are confident that most of our main points were selected although we cannot confirm if they were all brought across correctly and without judging statements. To test this, it would have been necessary to also test students’ performance in classes from teachers participating in the workshop versus our instructed classes, which was not feasible for 93 teachers across Austria.

Although we asked teachers in Austria for the long term post-test not to mention specific terms, it is possible that a teacher or a student made a well-intentioned suggestion (e.g., “remember the Lab Day where we did…”) that could have altered the data. In general, feedback from teachers and students still seems to be limited when written. Students' changes in behavior or thinking about the environment are not directly measurable as those will be long-term effects.

In general, the positive students’ test-results might not be completely representative for a typical high school student as the selection method was not random. For the students’ classes, one of the teachers we contacted for the project was already known to be interested in the subject and generally teachers would not participate if they think geosciences to be an unimportant subject. Teachers who volunteered may have self-selected for a favorable predisposition of the topic.

8.7. Implications

To emphasize the varied range of application and the linkage among several disciplines such as physics, biology and chemistry, successful geoscience education needs to combine modern educational tools with applied up-to-date science. This could be an important strategy to address and attract future geoscientists in the classroom and enhance the passion for science by making geoscience more visible - and also support and attract teachers for interdisciplinary teaching (Hattie, 2003).

We feel that providing a workshop for teachers where they were able to take on the role of students and ask questions but also familiarize themselves with the material kit in an informal setting helped engage them in the topic. For those teachers that cannot participate in professional development, an extensive background workbook with ready-to-use worksheets should always be available.

Attending the workshop with other teachers also sparked new ideas for teacher collaborations or project work. It could be beneficial to have workshops for colleagues from the same school to further foster teacher collaboration and thus improve interdisciplinary teaching at schools, especially when it comes to broad and complex topic regarding sustainability.

It seemed to have a positive influence on teachers to engage them in a subject that personally interested them – a subject which is not usually part of the standard curriculum and “something new and exciting”. This could also lead to collaborations with a science center nearby. Thus, we suggest that teacher workshops which encompass up-to-date topics, include a reference to daily life and also inform teachers in an engaging way. This might affect their teaching and thus help students getting access to more advanced topics.

By having students investigate the science and facts behind the issues and by emphasizing problem-based thinking, we can sensitize students for resources in their daily lives. This might eventually lead to a change in behavior at some point, after it has been repeatedly implemented in different settings.

Oral teacher feedback suggested that the mere bulk of new input (students were targeted with a large amount of new concepts, new information, new setting, unknown scientist as teacher and a different topic) might have been too much in one instruction module. Instead, the repetition and elaboration of concepts from our module in other lessons, other contexts, and other grades is needed as the Next Generation Science Standard suggests (NGSS, 2013).

In our case study with students, due to time restrictions, we discussed the topics of each commodity via a presentation where we already provided much of this information. Ideally and with no time restriction, this would be information acquired by students. A way to sum up the acquired knowledge - our resource intensive consumer behavior, the ecological and social effects of mining for mineral resources, the importance of preserving resources to maintain our system Earth, and our living standards and possible solutions such as recycling - can be debated in a role playing game, which we have tried in stages following the case study. Identities students may take on include one or more of the following and can easily be expanded: a mining worker, a farmer who has been deprived of land for a mine, an environmental protection activist, a manufacturer of different parts, a development aid worker, a factory worker, a global organization for sustainable sourcing, a warlord of a conflict county, a trader of commodities, a consumer, a recycler, a vendor, a politician, and so on. It is important that students lead the discussion themselves. During the entire module, there should be no intervention or judgment by the teacher (such as: ”see how bad this is” or “we should not buy a new phone so often”). Rather, the teacher should - if at all necessary - only guide students with questions to come up with their own conclusions that represent their own realistic approach.

We recommend the part of the module implementing the cards should start from grade 9 and older, in order to have the necessary chemistry background needed to understand the answers. For younger students, a discussion guided by the teacher seems to be more appropriate – something we have tested with classes following our case study. We therefore place the presented module for a targeted age group starting at grade 9, although parts of it can be used for younger students.

Continuous feedback from students and teachers helped refine the module and adapt it to the needs of students and teachers. The data suggest that many students learned and retained knowledge mainly from the practical exercises (disassembling the mobile phones) which stresses the necessity of hands-on exercises. The assessment results demonstrate that such a diverse, complex topic can be taught in school and some knowledge is retained over the short and long term. However, theoretical parts of the topic that had not been covered in hands-on exercises and are not repeated after the visit are not retained as well over longer timescales. We suggest reinforcing difficult concepts in multiple settings (i.e., out of school and in school) might have a stronger impact on learning. In general, we propose that conducting outreach with scientists (as we did in the students' study, where the first author, as a research scientist, taught the module) is a highly successful way of engaging students and familiarizing teachers with the pedagogical content knowledge, which in turn could play a role in fostering curiosity and an overall appreciation of science.

All our study limitations show that we mostly focused on adapting our module. For a complete investigation of the module and different learning types for the two countries, further research would be necessary.

Last but not least, we would like to cite the headline introduction of InTeGrate modules, which closely resembles our approach: Modules should be "hands-on, data-rich, and socially relevant geoscience activities" (InTeGrate, 2016).

8.8. Acknowledgements

The main part of the project was funded by Kulturkontakt Austria, the Ministry of Education and Culture (BMUKK) and the Magistration of Vienna (MA7). We also thank the Industriellenvereinigung Wien for their funding. Small parts of the research were funded by the IASS Potsdam.

We very much appreciate the help of all the participating students and teachers, especially Rita Chang from Wellesley High School, Massachusetts.

8.9. Authorship contribution

B. Bookhagen - Conceptualization, Methodology, Data curation, Interpretation, Writing - original draft.

C. Koeberl - Writing - review & editing; Supervision.

L. Juan - Methodology, Interpretation, Writing - review & editing.

D. DeRosa - Writing - review & editing; Supervision.

8.10. Reference list

1. AAAS, American Association for the Advancement of Science (1993). Benchmarks for Science Literacy. Oxford University Press, USA
2. Barab, S.A., and Luehmann, A.L. (2003). Building sustainable science curriculum: Acknowledging and accommodating local adaptation. Science Education, 87(4), 454-467. doi: 10.1002/sce.10083
3. BMB, Bundesministerium für Bildung (2007). (Austrian Federal Ministry for Education, in German; from https://www.bmb.gv.at/ministerium/ministerin/reden/bildungsenquete.html accessed Jan 2017
4. BMUB, Bundesministerium für Umwelt, Bau und Reaktorsicherheit (2009). Leitbild der Nachhaltigkeit in der Schule (German Federal Ministry of Environment: Sustainabilty in schools) from http://www.umwelt-im-unterricht.de/hintergrund/das-leitbild-nachhaltigkeit-in-der-schule/ accessed Jan 2017
5. Bloom, K. (1956). Taxonomy of Educational Objectives: The Classification of Educational Goals. New York: Longmans, Green
6. Bookhagen, B., Nordmann, J., Dyrnes, I., Stengel, O., & Schmidt, N.-H. (2013). Acceptance of Mobile Phone Return Programs: A Case Study Based Analysis. Paper presented at the ICT4S 2013, ETH Zurich, University of Zurich and Empa, Swiss Federal Laboratories for Materials Science and Technology
7. Bookhagen, B., McLean, N., Buchwaldt, R., Rioux, M., Dudas, F. and Bowring, S. (2014). EARTHTIME: Teaching Geochronology to High School Students in the USA. In V. C. Tong, Geoscience Research and Outreach. Schools and Public Engagement (S. 171-189). Dordrecht: Springer
8. Breslyn, W., & McGinnis, J. R. (2012). A comparison of exemplary biology, chemistry, earth science, and physics teachers' conceptions and enactment of inquiry. Science Education, 96(1), 48-77
9. Coe, R. (2002). It's the effect size, stupid: What “effect size” is and why it is important. Von Ppaer presented at the Annual Conference of the British Educational Research Association; from http://www.leeds.ac.uk/educol/documents/00002182 accessed Jan 2017
10. Cohen. (1990). Things I have learned (so far). American Psychologist, S. 1304–1312
11. Creswell, J (2002). Educational Research: Planning, Conducting, and Evaluating. Prentice Hall, NJ.
12. EPA, US Environmental Protection Agency (2011). Electronics Waste Management in the United States Through 2009; from http://www2.epa.gov/recycle

13. ESLI, Earth Science Literacy Initiative. (2010). Earth Science Literacy Principles, from http://www.earthscienceliteracy.org/ accessed Jan 2017
14. Edugroup (Austrian Education Group). Youth Media Study 2015; from
15. https://www.edugroup.at/innovation/forschung/jugend-medien-studie/detail/4-ooe-jugend-medien-studie-2015.html accessed Jan 2017
16. Eurostat (2015). Waste statistics - electrical and electronic equipment; from
17. http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment accessed Jan 2017
18. Feinstein, N.W. and Kirchgasler, K.L. (2015). Sustainability in Science Education? How the Next Generation Science Standards Approach Sustainability, and Why It Matters. Science Education, 99(1), 121-144. doi: 10.1002/sce.21137
19. Foley, J.M., Bruno, B.C., Tolman, R.T., Kagami, R.S., Hsia, M.H., Mayer, B. and Inazu, J.K. (2013). C-MORE Science Kits as a Classroom Learning Tool. Journal of Geoscience Education: August 2013, Vol. 61, No. 3, pp. 256-267
20. Gartner (2016). Worldwide Mobile Phone Sales; from http://www.gartner.com/newsroom/id/3187134 accessed Jan 2017
21. Gosselin, D. (2013). Transforming the Teaching of Geoscience and Sustainability. *EOS*, S. Vol. 94, No. 25.
22. Hagelüken, C. (2010). Wir brauchen ein globale Recyclingwirtschaft, exerts from a talk given in Vienna; from http://www.nachhaltigwirtschaften.at/nw_pdf/events/20101011_rohstoffversorgung_christian_hagelueken.pdf accessed Jan 2017
23. Hattie, J.A.C. (2003). Teachers make a difference: What is the research evidence? Paper presented at the Building Teacher Quality: What does the research tell us ACER Research Conference, Melbourne, Australia. Retrieved from http://research.acer.edu.au/research_conference_2003/4/
24. Hooper-Greenhill, E. (2007). Museums and Education: Purpose, Pedagogy, Performance: Routledge.
25. InTeGrate (2016). Interdisciplinary Teaching about Earth for a Sustainable Future; from http://serc.carleton.edu/integrate/index.html accessed Jan 2017
26. I-TECH, I. T. (2008). Guidelins for pre- and post-testing: A technical implementation guide; from http://www.go2itech.org/resources/technical-implementation-guides/TIG2.GuidelinesTesting.pdf accessed Jan 2017
27. Jones, S. a. (2010). Sustainablity education: Perspectives across Higher Education. London: Earthscan.

28. Locke, S., Libarkin, J., & Chang, C.-Y. (2012). Geoscience Education and Global Development. Journal of Geoscience Education, 60(3), 199-200. doi: 10.5408/1089-9995-60.3.199
29. MiTEP, Michigian Teacher Expert Program (2010). MiTEP List of Common Geoscience Misconceptions; from http://mitep.mspnet.org/index.cfm/22600 accessed Jan 2017
30. NCES, National Center for Education Statistics (2013). Performance of U.S. 15-Year-Old Students in Mathematics, Science, and Reading Literacy in an International Context, from https://nces.ed.gov/pubs2014/2014024rev.pdf accessed Jan 2017
31. NGSS, Next Generation Science Standards. (2013). Appendix G - Cross cutting concepts; from http://www.nextgenscience.org/sites/default/files/Appendix%20G%20-%20Crosscutting%20Concepts%20FINAL%20edited%204.10.13.pdf accessed Jan 2017
32. NRC, National Research Council (1997). Science teaching reconsidered. National Academy Press
33. NRC, National Research Council (2012). A Framework for K12 Science Education. Practices, Crosscutting Concepts and Core Ideas from http://www.nap.edu/read/13165/chapter/1 accessed Jan 2017
34. NSF, National Science Foundation (1996). Shaping the future: New expectations for undergraduate education in science, mathematics, engineering, and technology. NSF report, 92 pages. Arlington, VA
35. Nulty, D. (2008). The adequacy of response rates to online and paper surveys: what can be done?. Assessment & Evaluation in Higher Education, 33 (3), 301 - 314; from https://www.uaf.edu/files/uafgov/fsadmin-nulty5-19-10.pdf accessed Jan 2017
36. OECD Environment Directorate, Organization for Economic Cooperation and Development (2010). Materials Case Study 1: Critical Metals and Mobile Devices; from http://www.oecd.org/env/waste/46132634.pdf accessed Jan 2017
37. PewResearchCenter (2017). Mobile Fact Sheet; from http://www.pewinternet.org/fact-sheet/mobile/ accessed Jan 2017
38. Piaget, J. (1967). Logique et Connaissance scientifique (Logic and Scientific knowledge). Encyclopédie de la Pléiade.
39. Punch, K. (1998). Introduction to Social Research: Quantitative and Qualitative Approaches, London, Sage
40. Ramey-Gassert, L., Walberg, H. J., & Walberg, H. J. (1994). Reexamining connections: Museums as science learning environments. Science Education, 78(4), 345-363. (PewResearchCenter, 2017)

41. Remillard J.T, H.-E. B., Lloyd G.M. (2009). Mathematics teachers at work: Connecting curriculum materials and classroom instruction: Routledge
42. Scharnhorst, W., Ludwig, C., Wochele, J. a., & Jolliet, O. (2007). Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment. Science of The Total Environment, 373(2–3), 576-584. doi: http://dx.doi.org/10.1016/j.scitotenv.2006.11.023
43. Silverstein, S.C., Dubner, J., Miller, J., Glied, S., & Loike, J.D. (2009). Teachers' Participation in Research Programs Improves Their Students' Achievement in Science. Science, 326(5951), 440-442. doi: 10.1126/science.1177344
44. Stir, J. (2006). Restructuring teacher education for sustainabilty: student involvement through a "strengths model". Journal of Cleaner Production, S. Vol. 14, Issue 9-11
45. Sullivan, G.M. and Feinn, R. (2012). Using Effect Size—or Why the P Value Is Not Enough. J Grad Med Educ, S. 4(3): 279–282
46. SWICO (2009). SWICO Recycling Switzerland - teacher material; from www.swicorecycling.ch/downloads/dokumente/lehrerkommentar.../1455 accessed Jan 2017
47. Tilbury, D. (1995). Environmental Education for Sustainability: defining the new focus of environmental education in the 1990s. Environmental Education Research. Volume 1, Issue 2
48. UNDP, United Nations Development Programme (2000). United Nations Development Programme Millennium Development Goals; from http://www.undp.org/content/undp/en/home/mdgoverview/ accessed Jan 2017
49. UNEP, United Nations Environment Program (2008). Mobile Phone Partnership Initiative (MPPI); from http://archive.basel.int/meetings/oewg/oewg7/docs/oewg07-inf07.pdf accessed Jan 2017
50. UNESCO (2010). Teaching and Learning for a Sustainable Future; from http://www.unesco.org/education/tlsf/mods/theme_d/mod23.html?panel=2#top accessed Jan 2017
51. USGS, US Geological Survey (2006). Fact Sheet Recycled Cell Phones; from http://pubs.usgs.gov/fs/2006/3097/ accessed Jan 2017
52. Watt, S., C. Simpson, C. McKillop, and Nunn, V. (2002). Electronic course surveys: does automating
53. feedback and reporting give better results? Assessment & Evaluation in Higher Education 27, no. 4: 325–337

8.11. Supplements

Instructions for Supplements 1c, 1d

We recommend the mineral identifications quiz (supplement 1c) to be printed in DIN A3 and laminated for repeated usage.

Supplement 1d, which is a list of the minerals resources represented in the box, should also be laminated for better handling and repeated usage and cut into single light grey and dark grey cards.

Safety Standard Measurements

If you wish to follow our steps with the minerals raw materials box, please always keep **standard**

laboratory security measurements in mind: Although none of the raw materials we used are toxic, please make sure by asking the supplier where you obtain your minerals from that this is the case for your minerals, too. Always remind students not to eat or lick on minerals and always have students wash their hands after the exercise.

When students disassemble the mobile phone, make sure they extract the battery first and never do any experiments with the battery.

Tell students to be careful when disassembling the phones with screwdrivers or sharp objects. When time is limited, we found that removing the screws beforehand (or not putting them back in) helped in speeding up the process. Most of the older mobile phones can be disassembled multiple times if students take care in not breaking anything.

Supplement 1a)

Teaching Instructions Mobile Phone Mineral Resource Box

1. Disassemble a mobile phone and fill in the table:

a) Which parts do you find in a mobile phone?

b) What materials are the parts made up of? Discuss where the materials come from.

Parts	Material

Supplement 1b)

Mineral Identification Quiz and cards

1. Use the **Mineral Identification Quiz** and determine the minerals/rocks (put them right

next to their name)

2. Sort the correct cards to the minerals. Each mineral should get one light grey card for

„Element/Resource“ and one dark grey card for „Usage in Mobile Phone“. Use the bold headlines as path.

3. Sort the parts from the disassembled mobile phone to their corresponding mineral(s).

Please note:

Always keep standard laboratory security measurements in mind: Although none of the raw materials are toxic, do not eat or lick on minerals and always wash your hands after the exercise.

Name the rocks and minerals!

1. Color Start by placing all minerals in two groups according to their color.!	2. Appearance In which form does the rock/mineral appear?	3. Magnetisms Is the rock magnetic? Use the magnet in the box.	4. Smell When scratching it with your fingernail, does the rock smell like oil?	5. Streak Which color of streak leaves the rock on porcellain or paperr?	5. Hardness Which rock leaves a scratch on the other rock and is therefore harder?	Name
Group 1: lighter colors (purple, red, translucent) or multicolored	Powder					Clay
	Thin lamina					Gold
	Other	No	No oily smell	reddisch-brown		Bauxite
				grey-green		Chalkopyrite
				No colored-streak	Leaves a scratch on the other mineral	Quartz
					Is softer than the other mineral	Lepidolite
Group 2: Dark colores (grey and brown)	Granules (little round pellets)					Silicon
	Other	Yes				Magnetite
		No	Oily smell			Oilshale
			No	Leaves a scratch on the other mineral		Silicon
				Is softer than the other mineral		„Coltan“

Supplement 1d

Cards for quiz game, cut cells into cards and laminate them.
Cards are to be matched with and laid next to the identified mineral from the board game; each mineral gets one light grey card and one dark grey card.

Raw Material	Usage in Mobile Phone
Iron	Little screws and bolts
Copper	Cables and connectors, sheeted in printed circuit board, etc.
Gold	Corrosion resistant contacts and thin bondwires
Aluminum	Thin covers/plates on printed circuit board
Silicon	Microchips and processors; glass for display
Lithium	Battery
Tantalum	Electronic capacitors
Oil shale	plastics in case
Clay minerals	Isolators, in multilayered capacitors

Supplement 2: List of elements that can be part of a mobile phone

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**Lr	Rf	Db	Sg	Bh	Hs	Mt									

*Lanthanonids	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
**Actinoids	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Please keep in mind that most elements only occur in tiny amounts in a mobile phone and that different phone models (especially year of model-making) vary in content.

Some metals that make up the main part of a mobile phone are e.g., copper, silicon, aluminum, magnesium, iron and tin.

Supplement 3

The teacher questionnaires (study 1) included:

1. Did you find the prepared material (material kit, power point presentation, teacher brochure with

prepared worksheets) relevant for your curricula?

2. Which of the materials did you already use or plan on using?

Material kit: presentation: teacher brochure: worksheets:

3. Which thematic aspects did you use the material for?

Subject: class/age group: thematic aspect:

4. Did you find the mineral resource box supportive or do you think disassembling the phone itself would

be sufficient?

5. Did you find the teacher workshop as a preparation for using the material kit useful?

6. Would you have used the hands-on material without the preparation workshop?

Student questions (study 2) included:

1. Name some raw materials that can be found in a cell phone.

2. Do you think that the USA (Austria respectively) produces all raw materials and commodities needed to

manufacture our goods?

3. What is plastic made up of?

4. Why should cell phones be recycled?

5. Specifically which parts of a cell phone need to be carefully recycled and why?

6. How would you define the term "sustainability"?

Qualitative questions with open ended responses (Posttests only):

7. Which information did you find most interesting today?

8. How would you explain to a friend that unused old cell phones should not be left in the drawer?

9. Any other feedback and comments are appreciated.

Supplement 4

Resources most named by students in question 1

Vienna Pre-test	total n=209	male n=90	female n=119
	in %		
plastics	62	51	46
metals	55	39	47
copper	34	36	18
gold	29	31	15
aluminum	18	17	12
glass	16	17	9
iron	16	13	12
crude oil	12	5	13
silver	11	11	6
lithium	6	8	2

Vienna Post-test	total n=209	male n=90	female n=119
	in %		
gold	75	67	53
silver	60	51	45
plastics	52	39	44
copper	51	46	36
metals	47	14	59
silicon	43	41	28
lithium	41	30	36
aluminum	37	30	30
iron	29	22	25
crude oil	24	19	20

Boston Pre-test	total n=207	male n=102	female n=105
	in %		
plastics	26	26	27
metals	22	15	31
copper	19	29	9
iron	14	19	8
aluminum	10	14	7
glass	9	13	6
gold	6	9	4
silicon	6	11	2
silver	6	10	2
lithium	5	7	3

Boston Post-test	total n=207	male n=102	female n=105
	in %		
gold	63	74	62
silicon	53	62	52
copper	50	48	61
aluminum	41	43	46
iron	38	40	41
silver	38	37	44
lithium	28	28	31
plastics	23	23	27
Quarz	10	12	9
metals	9	6	13

Supplement 5

Summarized answers (students)

Vienna

	Pre-test	Post-test	Post-Post-test
Q1 correct in %	79	96	96
Q2 correct in %	95	94	95
Q3 correct in %	39	87	77

Boston

	Pre-test	Post-test
Q1 correct in %	70	98
Q2 correct in %	90	91
Q3 correct in %	16	80

The table summarizes the correct answers for Vienna and Boston for all three questions 1-3. Question 3 (what is plastics made up of) was the question most answered incorrectly in both countries in the pretest (only correct for 39% in Vienna and 16 % in the US). Question 1 and 2 had a very high rate in correctness in Vienna in the post-test (both above 95%) and question 3 was still answered correct by 86%.

9. Recapitulation

Smartphones contain many important metals and due to high sales numbers yet low recycling rates, they are representative devices when it comes to topics such as resource use, potential urban mining for metal supply, sustainability issues, and consumer behavior. As part of WEEE, they have been addressed in several studies, either focusing on metal content, recycling possibilities, and also options to promote take-back actions. Yet, detailed metal content of current smartphone devices has not been available due to the complex built and the need for elaborate analytical methods. In this study, a new analytical method was developed and validated to determine 57 metallic elements with one digestion protocol. This method lead to the answer of the first research question: **Which metallic elements can be found in smartphones and which quantities?**

Result showed that 57 metallic elements occur in smartphones; yet many of them occur in only very small amounts and are mostly located on the printed circuit board. The ten most abundant elements comprise already 93 % of the weight of the investigated metallic elements; these are iron, silicon, magnesium, aluminum, copper, nickel, chromium, tin, zinc, and strontium.

To further investigate the potentials for recycling and circularity questions for our future supply, the important technology metals cobalt, copper, gallium, germanium, gold, indium, palladium, platinum, the Rare Earth elements, and tantalum were further investigated by comparing their content in smartphones with currently mined ores and discussing their future potentials for recycling. These data have not existed prior to this study in this detail and answered the second research question: **Which of these are the most important metallic elements in smartphones with respect to economic importance, potential supply risks, sustainability, and recycling?**

Smartphones may look small when investigating one device, but the vast amount of sold devices have shown a significant impact on metallic resource use. For example, the gallium contained in all 7.42 billion smartphones sold in 2012-2017 could potentially supply the current global demand for 91 days. Gold is the most economically important metallic element and constitutes approximately 70 % of the complete metallic value of a smartphone. Also, copper, palladium, platinum and silver are of (lesser) importance for recycling. The specialty metals such as cobalt, indium, Rare Earth elements, and tantalum are currently not of interest for smartphone recycling, although some of them occur in amounts comparatively higher than in primary ores. These results can be used for detailed investigations for further circularity concepts, e.g. for design-for-recycling strategies. Sustainability issues regarding extraction and recycling of metallic elements need to be further dealt with by global policies such as the Sustainable Development Goals and should be addressed by society as a whole.

With consumers playing an important part for improved recycling rates and purchasing choices, an educational outreach module was developed and combined with several teacher and students workshop, dealing with the issue: **How can consumers be sensitized for improved resource appreciation and smartphone recycling?**

The study indicated that sensitizing about metallic resources in smartphones through various repeated activities and informing about recycling possibilities is one key to improve recycling actions. The developed educational module and the material box was adapted by several educational institutions and is still being used.

10. Publication list

Peer reviewed publications:

Bookhagen B, Bastian D, Buchholz P, Faulstich M, Opper C, Prohaska T, Irrgeher J, Koeberl C (2020). Metallic resources in smartphones: demand, supply, recycling potentials. Resources Policy. Vol. 68. https://doi.org/10.1016/j.resourpol.2020.101750

Bookhagen B, Obermaier W, Opper C, Koeberl C, Hofmann T, Prohaska T, Irrgeher J (2018). Development of a versatile analytical protocol for the comprehensive determination of the elemental composition of smartphone compartments on the example of printed circuit boards. Analytical Methods. Vol. 10, pp. 3864-3871 https://doi.org/10.1039/C8AY01192C

Bookhagen B, Koeberl C, Juang L, and DeRosa DA (2017). Mineral Resources in Mobile Phones: A Case Study of Boston and Vienna Teachers and Students. Journal of Geoscience Education. Vol. 65, No. 2, pp. 113-125. https://doi.org/10.5408/16-151.1

Books, book chapters, and non-peer reviewed journals:

Bookhagen B, Dorner U, Damm S, Bergholtz J, Opper C, Irrgeher J, Prohaska T und Koeberl C (2018). Rohstoffe im Fokus. ReSource. Vol.2. Rhombos Verlag

Bookhagen B, Dorner U, Damm S, Bergholtz J, Opper C, Irrgeher J, Prohaska T und Koeberl C (2018). Rohstoffverbrauch von Smartphones. In: Thiel S, Thomé-Kozmiensky E, Goldmann D (Eds). Recycling und Rohstoffe. Edition No 11. pages 519-531. Thomé-Kozmiensky Verlag. ISBN 978-3-944310-40-4.

Bookhagen B, Elbrunner E (2017). Rohstoffe in einem Mobiltelefon and Recycling von Mobiltelefonen (2 Chapter) In: Barnikel, F. und Summesberger, H. (Eds.). Diercke Natürliche Ressourcen. Methoden und Aufgaben. Pages 48-65. Braunschweig: Westermann. ISBN 978-3-14-109815-0.

Bookhagen B, Elbrunner E (2017). Rohstoffe in einem Mobiltelefon und Recycling von Mobiltelefonen. In: Barnikel, F. und Summesberger, H. (Eds.): Diercke Natürliche Ressourcen. Methoden und Aufgaben. Braunschweig: Westermann, p. 48-65. ISBN 978-3-14-109815-0

Bookhagen B, McLean N, Buchwaldt R, Rioux M, Dudas F, and Bowring S (2014). Earthtime: Teaching geochronology to high school students in the USA. In: Tong, VCH (Ed.). Geoscience Research and Outreach. Innovations in Science Education and Technology. Vol 21. Pages 171- 189. Springer, Dordrecht. www.doi.org/10.1007/978-94-007-6943-4_11

Nordmann J, Welfens MJ, Fischer D, Nemnich C, **Bookhagen** B, Bienge K, Niebert K (2014). Die Rohstoff-Expedition, Entdecke, was in (deinem) Handy steckt. 151 pages. Springer Spektrum. Didaktik der Naturwissenschaften, Berlin. www.doi.org/10.1007/978-3-662-44083-4

Bühn A, Niehoff S, **Bookhagen** B, Tobias M (2015). WEEE-Mining: A Research and Stakeholder Network on Material Flows in the Anthropocene. - In: Herzog, MA (Ed.), Economics of communication. ICT driven fairness and sustainability for local and global marketplaces, Berlin: GITO, p. 45-59. ISBN: 9783955451431

Welfens J, **Bookhagen B**, Nordmann J, **Reimann** S (2013). Rückgabe und Nutzung gebrauchter Handys. GAIA. 22/2: p. 128–131. Ökom-Verlag, München.

Bookhagen B (2012). Rohstoffkoffer: Was steckt im Handy? LehrerInnenbroschüre. 76 pages. Verlag Naturhistorisches Museum Wien, ISBN 978-3-902421-73-9

Poster/Conference Talks

Bookhagen B, Bastian D, Buchholz P, Faulstich M, Opper C, Prohaska T, Irrgeher J, Koeberl C (2020). A comprehensive metal investigation of smartphones for future recycling potentials. Poster. RecyDepotech Leoben. Conference Proceedings.

Irrgeher J, Bandoniene D, **Bookhagen** B, Gonzalez J, Opper C, Koerberl C, Pitha U, Scharf B & Prohaska T (2019). Technology-critical elements (TCEs): Source characterization and assessment of environmental exposure. Poster. 20. Tagung Fest-körperanalytik. TU Wien, Vienna, Austria.

Bookhagen B & Elbrunner H (2016). What is in your mobile phone? 35th International Geological Congress IGC, Geoscience Information for Teachers (GIFT). Cape Town, S-Africa. (Invited speaker)

Bookhagen (2015). Mineral resources in mobile phones - a hands-on tool for schools. EGU GIFT Teacher Workshop (General Assembly European Geosciences Union, Geosciences Information for Teachers). Vienna, Austria (Invited Speaker)

Bookhagen B, Nordmann J, Dyrnes I, Stengel O, Schmidt N-H (2013). Acceptance of Mobile Phone Return Programs: A Case Study Based Analysis. - In: Hilty LM, Aebischer B, Andersson G, Lohmann W (Eds.). International Conference on Information Communication Technologies for Sustainability (ICT4S). Conference Proceedings. Pages 59-64**.** http://dx.doi.org/10.3929/ethz-a-007337628

Bookhagen B, Bergner A, Schneider S, Ellger C (2014). GeoEd - A strategy for GeoEducation in Germany. Poster. Geophysical Research Abstracts, Vol. 16, EGU 2014-15761-1, 2014. General Assembly European Geosciences Union (EGU), Vienna, Austria. http://meetingorganizer.copernicus.org/EGU2014/EGU2014-15761-1.pdf

Bookhagen B, Mair A, Schaller G, Koeberl C (2012). A framework for high-school teacher support in Geosciences. Poster. General Assembly European Geosciences Union (EGU), Section: EOS Education Outreach). Vienna, Austria. 2012EGUGA..14.6204B

Bookhagen B, Mair A, Schaller G, Koeberl C (2011). “Mobile Phone Teaching Kit”: Connecting Geosciences and ”Everyday Applications” by providing Professional Training for Science Teachers. Poster. Conference 'Fragile Earth': GV-DGG-GSA Joint Meeting GeoMünchen. Munich, Germany.

Teaching materials, online:

Bookhagen/Nordmann/Niehoff/Welfens (2016). Hol die Gruftis raus. Verantwortung und Nachhaltigkeit. Mach mit! Staatskanzei Saarland (Ed). 208 pages. https://www.saarland.de/dokumente/thema_handyportal/2016_Materialien_Unterricht_Projekttage_Handy_Saarland_weiterfuehrende_Schulen.pdf

Bookhagen B, Fischer D, Nordmann J, Niehoff S (2014). Mobile Kommunikation: Umwelbewusst handeln. Materialien für Lehrkräfte. Informationszentrum für Mobilfunk (Ed.). http://www.izmf.de/de/node/101453/11280

11. Further work and publications

For the following four books and book chapters, only the cover page and basic information is presented, as publications are mostly in German and/or pages would go beyond the scope of this thesis.

Books /Book chapter (sorted by publication year):

Nordmann J, Welfens MJ, Fischer D, Nemnich C, **Bookhagen** B, Bienge K, Niebert K (2014). Die Rohstoff-Expedition, Entdecke, was in (deinem) Handy steckt. 151 pages. Springer Spektrum. Didaktik der Naturwissenschaften, Berlin. www.doi.org/10.1007/978-3-662-44083-4

Bookhagen B, McLean N, Buchwaldt R, Rioux M, Dudas F, and Bowring S (2014). EARTHTIME: Teaching geochronology to high school students in the USA. In: Tong, VCH (Ed.), Geoscience Research and Outreach. Innovations in Science Education and Technology. Vol 21. Pages 171- 189. Springer, Dordrecht.

Bookhagen B, Elbrunner E (2017). Rohstoffe in einem Mobiltelefon and Recycling von Mobiltelefonen (2 Chapter) In: Barnikel, F. und Summesberger, H. (Eds.). Diercke Natürliche Ressourcen. Methoden und Aufgaben. Pages 48-65. Braunschweig: Westermann. ISBN 978-3-14-109815-0.

Bookhagen B, Dorner U, Damm S, Bergholtz J, Opper C, Irrgeher J, Prohaska T und Koeberl C (2018). Rohstoffverbrauch von Smartphones. In: Thiel S, Thomé-Kozmiensky E, Goldmann D (Eds). Recycling und Rohstoffe. Edition No 11. pages 519-531. Thomé-Kozmiensky Verlag. ISBN 978-3-944310-40-4.

v

Vorwort

Mit den Wissenschaftsjahren bietet das Bundesministerium für Bildung und Forschung (BMBF) mit Unterstützung der Initiative *Wissenschaft im Dialog* (WiD) eine öffentliche Bühne für den Austausch zwischen Wissenschaft und allgemeiner Öffentlichkeit. Ziel ist es, neue Forschungsergebnisse und aktuelle wissenschaftliche Herausforderungen einem größeren Publikum bekannt zu machen, den Dialog darüber zu fördern sowie speziell Kinder und Jugendliche für wissenschaftliche Themen zu begeistern.

Im Wissenschaftsjahr 2012 – Zukunftsprojekt Erde, das die gesellschaftliche Debatte über Ziele, Herausforderungen und Aktionsfelder einer nachhaltigen Entwicklung förderte, gelang das besonders erfolgreich mit der Aktion „Die Rohstoff-Expedition – Entdecke, was in (d)einem Handy steckt!". Ausgangspunkt war ein vom BMBF gefördertes Forschungsvorhaben zum Thema „Rückgabe und Nutzung gebrauchter Handys", das vom Wuppertal Institut für Klima, Umwelt, Energie und dem IASS Potsdam – Institute for Advanced Sustainability Studies durchgeführt wurde. Die Ergebnisse des Forschungsprojektes bildeten die inhaltliche Basis für die Rohstoff-Expedition und die vorliegenden Lern- und Arbeitsmaterialien.

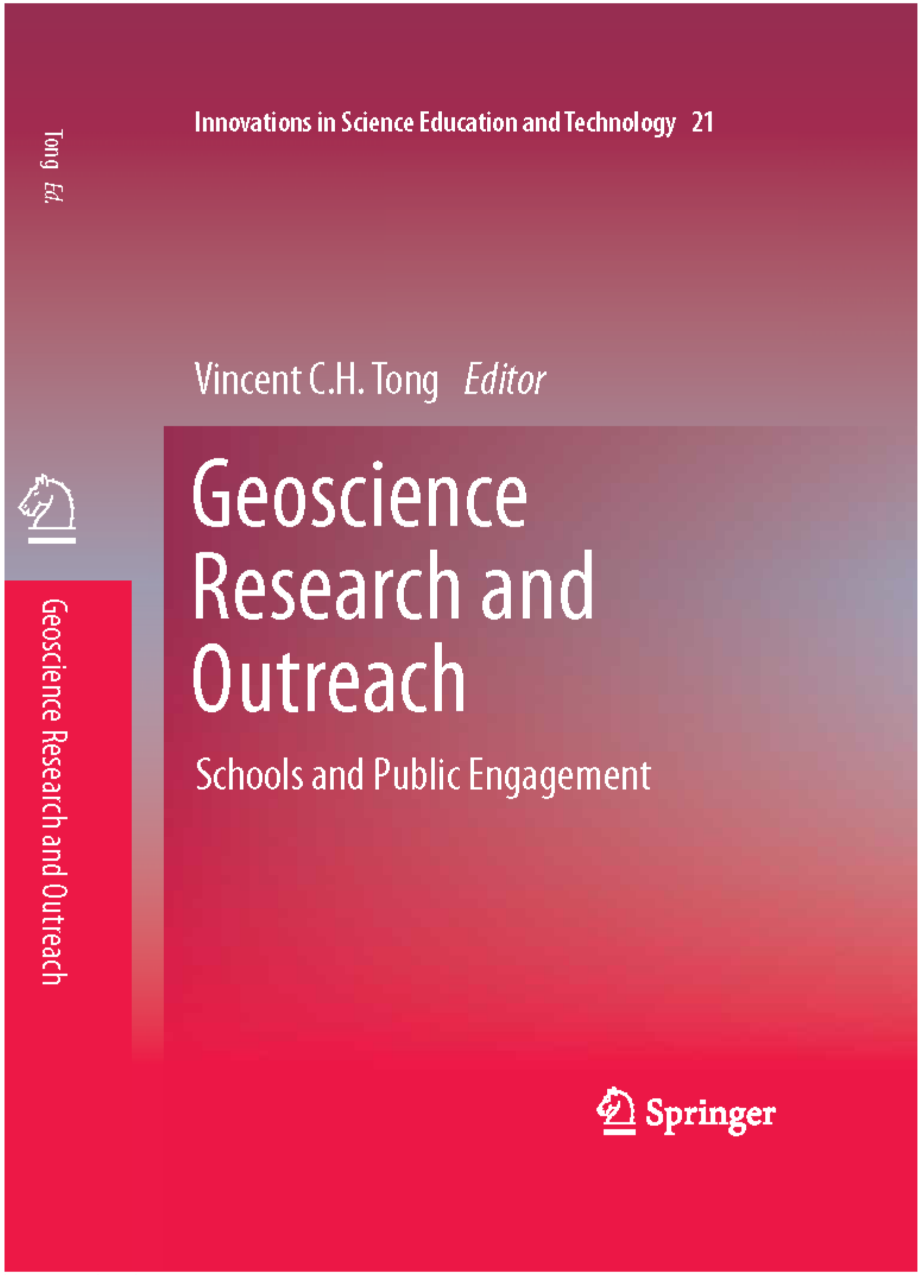
Die Rohstoff-Expedition startete im August 2012 in Zusammenarbeit mit den deutschen Netzanbietern Telekom Deutschland, E-Plus Gruppe, Telefónica Germany und Vodafone D2 sowie dem Verband zur Rücknahme und Verwertung von Elektro- und Elektronikaltgeräten (vere).

An der bundesweiten Sammelaktion von Alt-Handys nahmen bis März 2013 mehr als 1.600 Schulen und die vier großen Netzanbieter teil. Insgesamt wurden im Rahmen der „Rohstoff-Expedition" 65.090 Altgeräte gesammelt.

Das vorliegende Material ist eine aktualisierte und erweiterte Neuauflage. Es enthält ausführliche fachdidaktische Einführungen und Anknüpfungspunkte für den Einsatz in verschiedenen Unterrichtsfächern. Es geht insbesondere um den ökologischen Rucksack von Mobiltelefonen, den Ressourcenverbrauch von der Entstehung über die Nutzung bis hin zu Recycling und Wiederverwertung von Mobiltelefonen sowie um fundierte Handlungsanleitungen für ein individuelles ressourcenschonendes, sozial verträgliches Konsumverhalten. Somit werden die drei zentralen Leitfragen des Wissenschaftsjahres 2012 – Zukunftsprojekt Erde thematisiert: Wie wollen wir leben? Wie müssen wir wirtschaften? Und wie können wir unsere Umwelt bewahren?

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Wissenschaftsjahr 2012
Zukunftsprojekt ERDE
Eine Initiative des Bundesministeriums für Bildung und Forschung



EARTHTIME: Teaching Geochronology to High School Students in the USA

Britta Bookhagen, Noah McLean, Robert Buchwaldt, Matthew Rioux, Francis Dudás, and Samuel Bowring

1 Introduction

1.1 Why Teach Deep Time in School?

There is widespread recognition among scientists and education policymakers that student engagement in science must be improved. In order to maintain our technological standard, we need to ensure a scientifically literate society and continued contributions by competent scientists (American Geophysical Union 1994; National Science Foundation 1996; National Research Council 1997; National Science Board 2002, 2003). Geologic time ("Deep Time") is an important concept in geology, as already established by Hutton 1788 and Lyell 1830, giving a logical timescale to many Earth processes and events. Understanding the timing and rates of geologic processes is critical for understanding such diverse topics as the age and assembly of the Earth, plate tectonics, the timing and causes of mass extinctions, and the recurrence rates of volcanic activity and other natural hazards. Because geologic time and geochronology integrate elements of chemistry, physics, biology, and mathematics, teaching "Deep Time" provides an opportunity to introduce students to a key scientific concept that integrates knowledge from a diverse range of disciplines.

Research has demonstrated that several common preconceptions in science should be individually targeted. Project 2061, an initiative of the American Association for the Advancement of Science (AAAS, 2009), was founded in 1985 to advance literacy in science and has included more than a decade of research and development on preconceptions in science. Philips (1991) confirmed and summarized some earth science preconceptions that address time and time measurement

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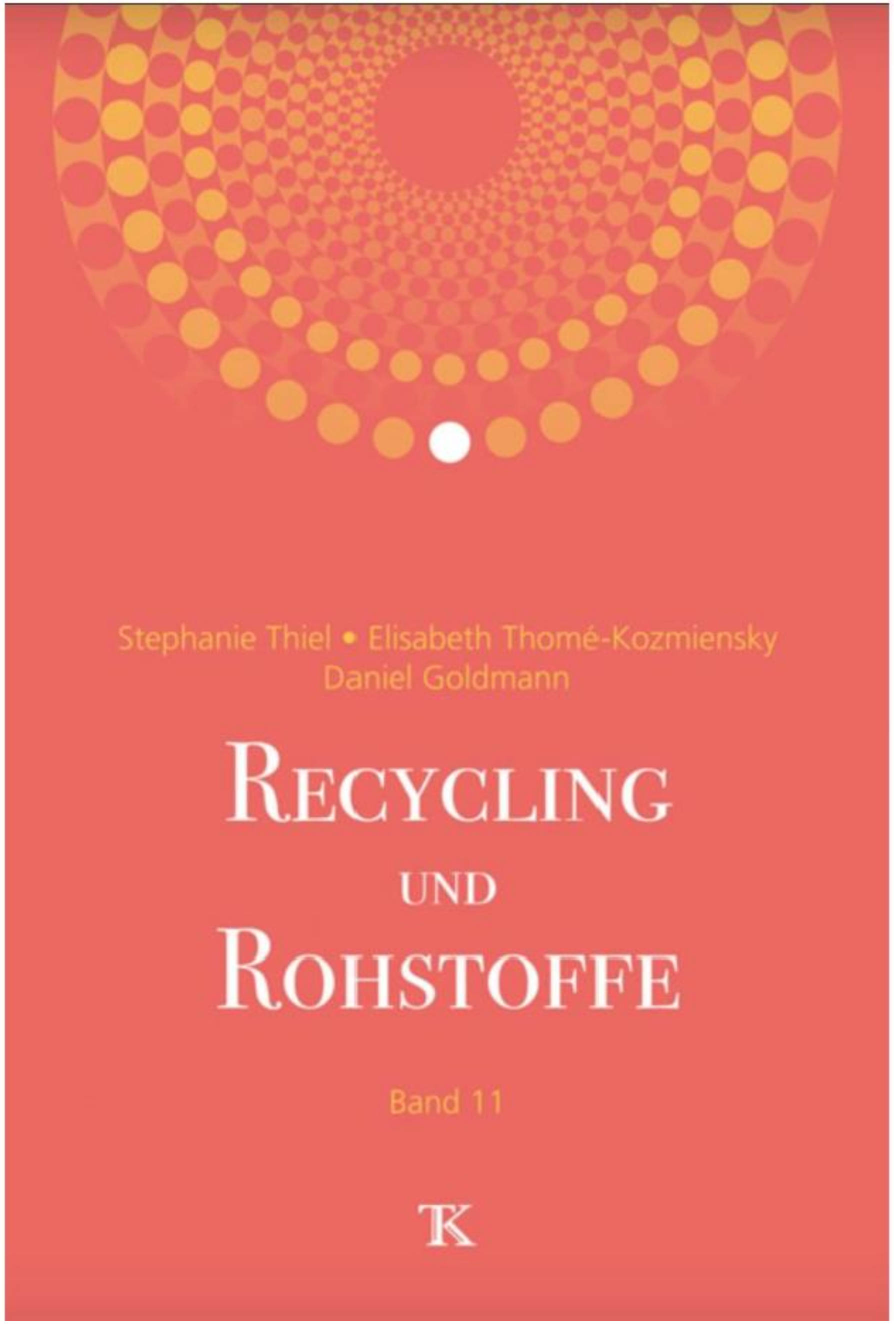
V.C.H. Tong (ed.), *Geoscience Research and Outreach: Schools and Public Engagement*, Innovations in Science Education and Technology 21, DOI 10.1007/978-94-007-6943-4_11, 171

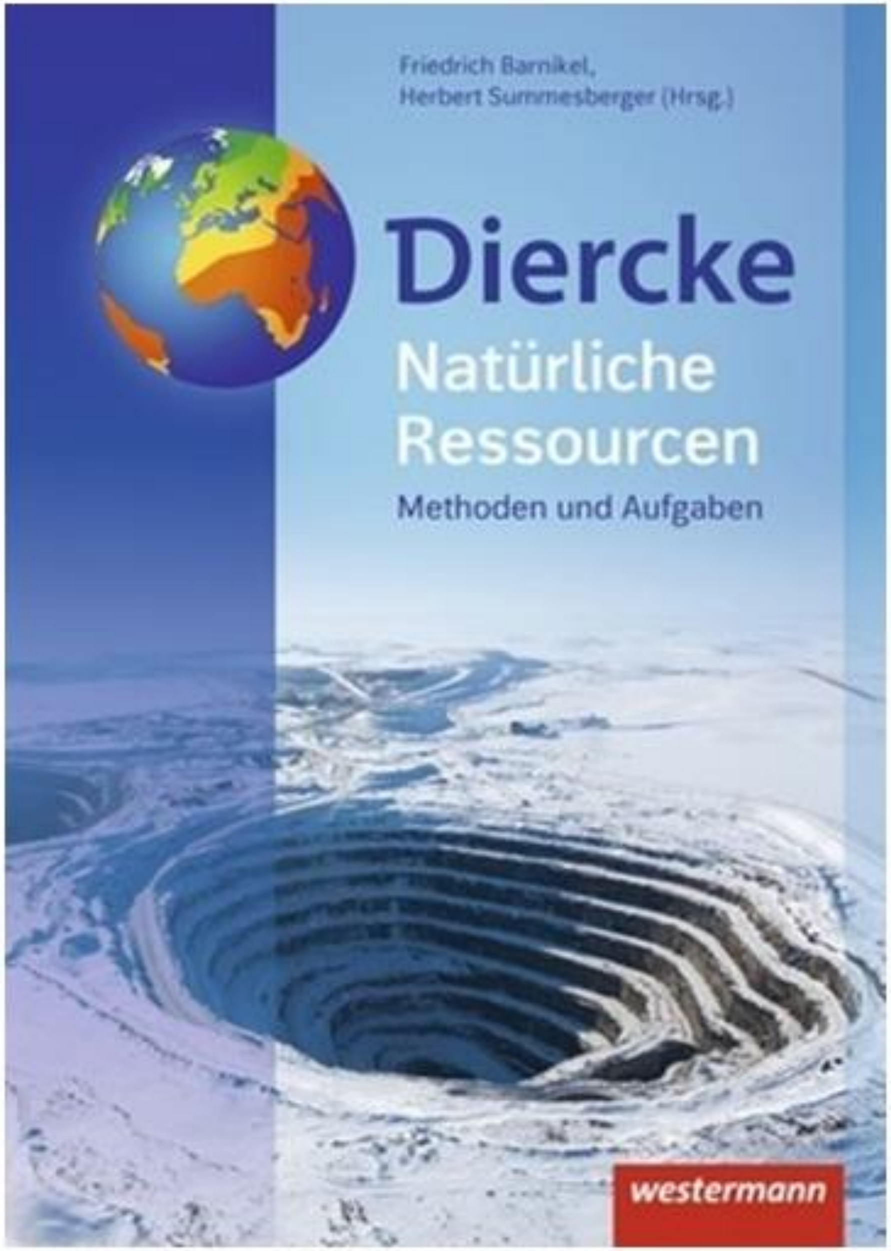


Rohstoffverbrauch von Smartphones

Britta Bookhagen, Ulrike Dorner, Sophie Damm, Jana Bergholtz, Christine Opper, Johanna Irrgeher, Thomas Prohaska und Christian Koeberl

In den globalen Wertschöpfungsketten ist die Herkunft der Rohstoffe und die Zusammensetzung der Konsumgüter kaum noch nachvollziehbar. Die Transparenz entlang der Wertschöpfungskette wird jedoch für Produzenten und Konsumenten immer bedeutender. EU-Direktiven (WEEE, RoHS und REACH) und internationale Gesetze und Richtlinien (z.B. U.S. Dodd Frank Act, Section 1502 geltend seit 2012, die OECD-Leitsätze für die Erfüllung der Sorgfaltspflicht von 2013 und das EU Conflict Minerals Agreement von 2016) haben das Thema vermehrt in die Öffentlichkeit gerückt [8, 11, 21, 23, 31]. Aber auch eine durch Konsumenten und Organisationen geforderte zunehmende Relevanz eines verantwortungsvollen unternehmerischen Handelns (Corporate Social Responsibility und Producer Responsibility), sowie die mediale Aufmerksamkeit für mögliche negative Auswirkungen der Produktion entlang der Lieferketten (z.B. Blood in the Mobile, 2009; Amnesty Bericht zu Kobalt, 2016) spielen in diesem Zusammenhang eine immer größere Rolle [1, 6]. Einerseits sind Themen wie die Rohstoffe aus Konfliktregionen und nachhaltiger Bergbau, die soziale und ökologische Aspekte des Rohstoffabbaus und der Produktionsstufen mit einbeziehen von Belang, andererseits geht es darum, Inhaltsstoffe zu bestimmen und Rohstoffe möglichst effizient zu nutzen sowie das Recycling als alternative Rohstoffquelle zu stärken. Trotz verschiedener bereits in Kraft getretener Maßnahmen gibt es noch viele Herausforderungen im Bereich der Umsetzung einer transparenten Wertschöpfungskette. Die Lieferketten sind oft komplex mit vielen Händlern und Zwischenhändlern, weshalb die Produzenten nicht immer alle Stationen der Kette kennen. Im Downstream-Bereich der Lieferkette gibt es spezielle Herausforderungen. Zusätzlich kommen laufend neue Geräte auf den Markt, deren exakte Zusammensetzung sich nicht eindeutig nachvollziehen lässt. Eine stetige Analyse der Inhaltsstoffe ist sehr aufwendig, daher können meist nur grobe Schätzwerte verwendet werden.

Elektro(nik)geräte



Inhalt | Diercke – Natürliche Ressourcen | 3

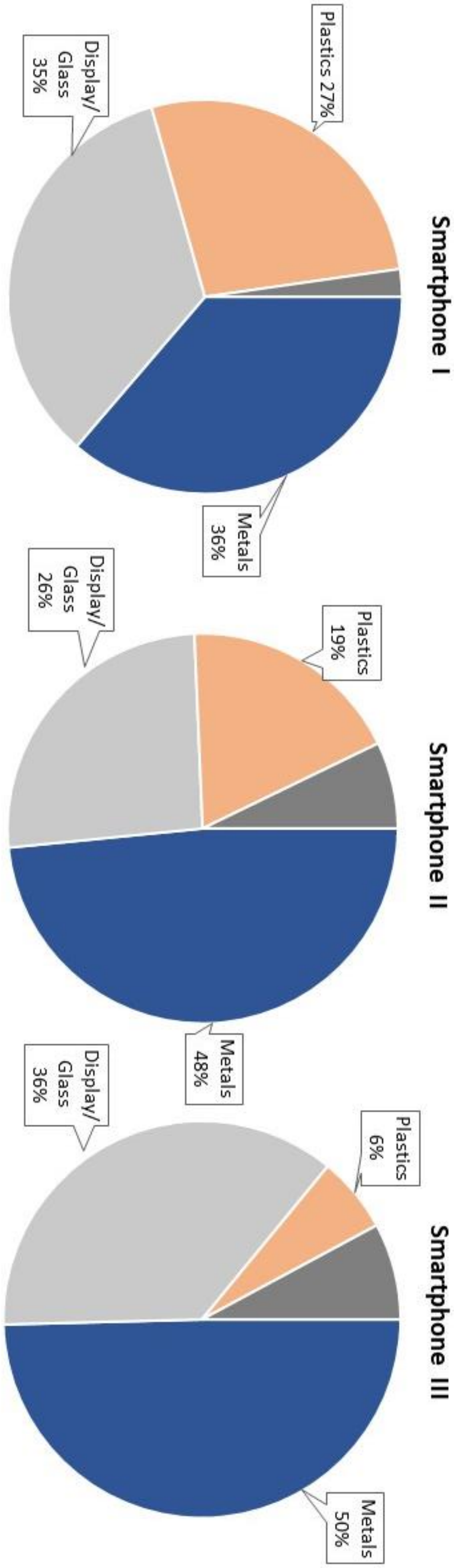
Inhalt

Acknowledgements

Throughout the writing of my dissertation, I have received a great deal of support and assistance. I would like to thank the following people, who helped make my work possible and supported me throughout the process:

- my supervisors Prof. Dr. Christian Köberl, Prof. Dr. Thomas Prohaska, Dr. Johanna Irrgeher
- Kulturkontakt Austria, Ministry of Education and Culture (BMUKK), Magistration of Vienna (MA7)
- Christine Opper
- Wolfgang Obermaier
- Dr. Dieter Mader, Prof. Dr. Thilo Hofman
- Dr. Jana Bergholtz
- Dr. Benjamin Sames
- Prof. Dr. Lutz Hecht
- Dr. Christian Hagelüken, Prof. Dr. Martin Faulstich, Prof. Dr. Daniel Goldmann, Dr. Asja Mrotzek-Blöß
- Prof. Dr. Susanne Rotter, Nathalie Korf, Dr. Maria Kletecka-Pulker, Dr. Esther Thiebaud, Dr. Sven Grieger
- Dr. Peter Buchholz, Dennis Bastian, Dr. Martin Schmitz, Ulrike Dorner, Maren Liedtke, Philip Schütte and other colleagues at BGR/DERA
- Agnes Mair, Monika Müller, Gertrude Schaller and other colleagues from nhm educational team
- Prof. Dr. Don de Rosa
- Prof. Dr. Linda Juang
- Silke Niehaus, Aneta Galek
- my friends Anja, Ewa, Gundi, Katrin, Meike, Natasha, Sabrina and Tina
- Prof. Dr. Bodo Bookhagen
- Dr. Maurus de la Rosa
- my parents Lore und Wilfried

Appendix I: Average composition of investigated smartphones (n=3)



Appendix IIa: Total amount of measured elements from entire smartphones

Total amount of measured elements from entire smartphones from three different manufacturers (n = 3) from averaged triplicates of each smartphone type. Uncertainties (u_c) correspond to total combined uncertainties (k = 1).

Element	Smartphone I		Smartphone II		Smartphone III		Average Smart-phone I-III	
	total amount /g	u_c /g	total amount /g	u_c /g	Total amount /g	u_c /g	Total amount /g	u_c /g
Ag	0.0113	0.0034	0.0154	0.0041	0.0069	0.0007	0.0112	0.0027
Al	4.063	0.0695	13.701	0.3309	2.295	0.1287	6.686	0.1764
As	0.00230	0.0001	0.00375	0.0017	0.00409	0.0002	0.00338	0.0006
Au	0.0165	0.0009	0.0146	0.0160	0.0194	0.0013	0.0168	0.0061
Ba	0.320	0.1300	0.470	0.1586	0.262	0.0086	0.351	0.0991
Bi	0.00065	0.0000	0.00035	0.0014	0.00065	0.0002	0.00055	0.00001
Co	0.0287	0.0064	0.0368	0.0055	0.1006	0.0018	0.0554	0.0006
Cr	0.00242	0.0001	0.07730	0.5418	5.99297	0.1314	2.02423	0.0046
Cu	4.58	0.1376	11.41	3.4786	3.83	0.0857	6.61	0.2245
Fe	3.949	0.0751	13.623	2.6904	31.66	0.5515	16.411	1.2340
Ga	0.00337	0.0001	0.01039	0.0022	0.01136	0.0003	0.00837	1.1057
Ge	0.00015	0.00003	0.00025	0.0004	0.00066	0.0000	0.00035	0.0009
Hf	0.00058	0.00004	0.00084	0.0004	0.00041	0.0001	0.00061	0.0002
Hg	0.00008	0.000001	0.00002	0.00001	0.00001	0.0000	0.00004	0.0002
In	0.00205	0.00005	0.00350	0.0015	0.00220	0.0009	0.00258	0.0000
Li	0.00054	0.00002	0.00086	0.0004	0.00132	0.00004	0.00091	0.0008
Mg	14.713	0.0863	6.799	0.0632	0.198	0.0165	7.237	0.0002
Mn	0.0594	0.0045	0.1996	0.0319	0.3026	0.0154	0.1872	0.0554
Mo	0.01185	0.0008	0.02998	0.0032	0.07090	0.0129	0.03758	0.0173
Nb	0.00299	0.0004	0.00357	0.0010	0.00604	0.0005	0.00420	0.0056
Ni	0.609	0.0107	3.289	0.5796	3.918	0.1052	2.605	0.0006
Pb	0.00593	0.0003	0.01476	0.0186	0.00889	0.0003	0.00986	0.2318
Pd	0.00123	0.0000	0.00231	0.0025	0.00220	0.0002	0.00191	0.0064
Pt	0.00087	0.0000	0.00025	0.0006	0.00032	0.0000	0.00048	0.0009
Sb	0.00016	0.0000	0.00085	0.0001	0.00052	0.0000	0.00051	0.0002
Si	8.073	0.0788	7.697	1.0575	12.047	0.2268	9.272	0.0000
Sn	0.511	0.0164	0.980	0.2984	0.43	0.0068	0.639	0.4544
Sr	0.5441	0.2054	0.6955	0.0421	0.09478	0.0242	0.4448	0.1072
Ta	0.0364	0.0028	0.0558	0.0772	0.028	0.0009	0.0402	0.0906
Ti	0.0823	0.0013	0.1722	0.0739	0.091	0.0073	0.1150	0.0270
V	0.00308	0.0003	0.01181	0.0025	0.02298	0.0025	0.01262	0.0275
W	0.5455	0.0042	0.1262	0.0158	0.0248	0.0025	0.2321	0.0018
Zn	0.1744	0.0073	1.65	0.0397	0.1289	0.0034	0.6520	0.0075
Zr	0.04872	0,0019	0.0491	0.0179	0.0141	0.0003	0.0378	0.0168
REE	0.265	0.007	0.332	0.008	0.313	0.005	0.303	0.007

Appendix IIb: Mass fraction of measured elements from entire smartphone

Mass fractions of measured elements from entire smartphones from three different manufacturers (n = 3) from averaged triplicates of each smartphone type. For uncertainties, see Appendix IIa.

Element	Smartphone I	Smartphone II	Smartphone III	Average Smartphone I-III
Ag	0.12 mg g^{-1}	0.12 mg g^{-1}	0.061 mg g^{-1}	0.101 mg g^{-1}
Al	43.61 mg g^{-1}	108.9 mg g^{-1}	20.23 mg g^{-1}	57.60 mg g^{-1}
As	29 µg g^{-1}	32 µg g^{-1}	37 µg g^{-1}	33 µg g^{-1}
Au	177 µg g^{-1}	116 µg g^{-1}	171 µg g^{-1}	155 µg g^{-1}
Ba	3.4 mg g^{-1}	3.7 mg g^{-1}	2.3 mg g^{-1}	3.2 mg g^{-1}
Be	0.3 µg g^{-1}	0.3 µg g^{-1}	0.1 µg g^{-1}	0.3 µg g^{-1}
Bi	7.0 µg g^{-1}	2.8 µg g^{-1}	5.8 µg g^{-1}	5.2 µg g^{-1}
Co	0.31 mg g^{-1}	0.29 mg g^{-1}	0.89 mg g^{-1}	0.50 mg g^{-1}
Cr	27 µg g^{-1}	616 µg g^{-1}	52.9 mg g^{-1}	17.8 mg g^{-1}
Cu	49 mg g^{-1}	91 mg g^{-1}	34 mg g^{-1}	58 mg g^{-1}
Fe	42.4 mg g^{-1}	108.4 mg g^{-1}	279 mg g^{-1}	143.3 mg g^{-1}
Ga	45 µg g^{-1}	96 µg g^{-1}	106 µg g^{-1}	82 µg g^{-1}
Ge	1.6 µg g^{-1}	2.0 µg g^{-1}	6 µg g^{-1}	3.1 µg g^{-1}
Hf	6.2 µg g^{-1}	6.7 µg g^{-1}	4 µg g^{-1}	5.5 µg g^{-1}
Hg	0.88 µg g^{-1}	0.12 µg g^{-1}	0.07 µg g^{-1}	0.36 µg g^{-1}
In	22 µg g^{-1}	28 µg g^{-1}	19 µg g^{-1}	23 µg g^{-1}
Li	5.8 µg g^{-1}	6.9 µg g^{-1}	1.6 µg g^{-1}	8.1 µg g^{-1}
Mg	157.94 mg g^{-1}	54.09 mg g^{-1}	1.75 mg g^{-1}	71.26 mg g^{-1}
Mn	0.638 mg g^{-1}	1.59 mg g^{-1}	2.7 mg g^{-1}	1.63 mg g^{-1}
Mo	128 µg g^{-1}	239 µg g^{-1}	626 µg g^{-1}	331 µg g^{-1}
Nb	53 µg g^{-1}	29 µg g^{-1}	74 µg g^{-1}	52 µg g^{-1}
Ni	6.6 mg g^{-1}	26.2 mg g^{-1}	35 mg g^{-1}	22.4 mg g^{-1}
Pb	64 µg g^{-1}	117 µg g^{-1}	78 µg g^{-1}	87 µg g^{-1}
Pd	13 µg g^{-1}	18 µg g^{-1}	19 µg g^{-1}	17 µg g^{-1}
Pt	9.3 µg g^{-1}	2.0 µg g^{-1}	2.8 µg g^{-1}	4.7 µg g^{-1}
Sb	1.8 µg g^{-1}	6.73 µg g^{-1}	4.6 µg g^{-1}	4.4 µg g^{-1}
Si	86.7 mg g^{-1}	61.2 mg g^{-1}	106.2 mg g^{-1}	84.7 mg g^{-1}
Sn	5.5 mg g^{-1}	7.8 mg g^{-1}	3.7 mg g^{-1}	5.7 mg g^{-1}
Sr	5.841 mg g^{-1}	5.532 mg g^{-1}	0.836 mg g^{-1}	4.07 mg g^{-1}
Ta	0.39 mg g^{-1}	0.44 mg g^{-1}	0.3 mg g^{-1}	0.36 mg g^{-1}
Ti	0.88 mg g^{-1}	1.37 mg g^{-1}	0.8 mg g^{-1}	1.02 mg g^{-1}
V	33 µg g^{-1}	93.9 µg g^{-1}	203 µg g^{-1}	110 µg g^{-1}
W	5.86 mg g^{-1}	1.004 mg g^{-1}	0.22 mg g^{-1}	2.36 mg g^{-1}
Zn	1.87 mg g^{-1}	13 mg g^{-1}	1.1 mg g^{-1}	5.4 mg g^{-1}
Zr	528 µg g^{-1}	398 µg g^{-1}	124.2 µg g^{-1}	350 µg g^{-1}
REE	2.843 mg g^{-1}	2.640 mg g^{-1}	2.763 mg g^{-1}	2.749 mg g^{-1}

Appendix III: Calculation for ore weight and metallic content in smartphone

Comparison of element content in smartphones (I) and averaged ore grades (II): (I) averaged from measured triplicates of three smartphones; (II) pure calculated element range in ores (low and high grade ores). III is the calculated partial weight of ores needed in order to produce the partial metal content in smartphones for each element. Sorted by descending element content in smartphones.

Element	I content of element in smartphone	II exemplary ores	III Ore grade [%]		IV Calculated ore weight for each metal content in smartphone [g]	
	in [%]		low grade ores	high grade ores	for low grade ores	for high grade ores
Fe	14.42	Hematite (Fe_2O_3)	48	72	33	22
Si	8.4	Quartz (SiO_2)	47	47	20	20
Mg	6.5	Dolomite $CaMg(CO_3)_2$	0.1	23	7237	31
Al	6.0	Bauxite ($Al_2O_3 \cdot nH_2O$)	0.27	1.8	2476	371
Cu	6.0	Chalcopyrite ($CuFeS_2$)	33	55	20	12
Ni	2.4	Limonite [(Fe,Ni)O(OH)]	0.1	5	2605	52
Cr	1.8	Chromite ($FeCr_2O_4$)	26	33	8	6
Sn	0.6	Cassiterite (SnO_2)	55	78	1	1
Zn	0.57	Sphalerite (ZnS)	3	17	21	4
Sr	0.40	Celestite ($SrSO_4$)	20	45	2	1
Ba	0.32	Baryte ($BaSO_4$)	59	59	1	1
REE	0.27	Monazite (Ce,La,Nd,Th) (PO_4,SiO_4)	0.0025	10	11898	3
W	0.21	Wolframite, $(Fe,Mn)WO_4$	0.18	0.95	127	24
Mn	0.17	Pyrolusite (MnO_2)	32	63	1	0
Ti	0.1038	Ilmenite $FeTiO_3$	26	56	0	0
Co	0.0454	Cobaltite (CoAsS)	0.03	0.66	168	8
Ta	0.0363	Tantalite (Mn,Fe) $(Ta,Nb)_2O_6$	0.018	0.036	223	112

Element	I content of element in smartphone	II exemplary ores	III Ore grade [%]		IV Calculated ore weight for each metal content in smartphone [g]	
	in [%]		low grade ores	high grade ores	for low grade ores	for high grade ores
Mo	0.0339	Molybdenite (MoS_2)	2	10	2	0.38
Zr	0.0337	Zircon ($ZrSiO_4$)	60	75	0	0.05
Au	0.0152	Au; by-product of Cu-ores	0.00003	0.00046	58230	3658
Ga	0.0076	By-product of bauxite	0.0057	0.0082	147	102
In	0.0023	By-product of sphalerite (Zn,Fe)S	0.0015	0.005	172	52
Pd	0.0017	By-product of Pt- and Ni-ores	0.000005	0.0014	38210	136
Sb	0.0005	Stibnite (Sb_2S_3)	19	71	<0.01	<0.01
Ge	0.0003	By-product of sphalerite (Zn,Fe)S	0.0068	0.085	5	0.4
V	0.0126	vanadiferous Titanomagnetite (Fe_{3-x}. Ti_xO_4)	0.42	2.5	3.01	0.50
Ag	0.0112	silver-bearing galena (PbS)	0.0097	0.045	115	25.10
Pb	0.0099	Galena (PbS)	1	17	0.99	0.06
Nb	0.0038	Columbite $(Mn,Fe)(Ta,Nb)_2O_6$	0.7	1.75	0.60	0.24
As	0.0031	Arsenopyrite (FeAsS)	0.3	10	1.13	0.03
Li	0.0008	Lepidolite $K(Li, Al, Rb)_2(Al, Si)_4O_{10}(F, OH)_2$	0.24	3.7	0.38	0.02
Pt	0.0005	Sperrylite ($PtAs_2$)	0.000003	0.0019	17020	27

Sum in [kg]	**138.7**	**4.7**

References, sorted by descending order of element content in smartphones:

Fe: USGS Iron ore statistics and information https://www.usgs.gov/centers/nmic/iron-ore-statistics-and-information accessed July 2020

Mg: DERA Rohstoffinformation 38 – Rohstoffrisikobewertung Magnesium. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-38.pdf accessed July 2020

Cu: Calvo G, Mudd G, Valero A, Valero A (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources. 5(4), 36; https://doi.org/10.3390/resources5040036 and

Mudd G; Weng Z; Jowitt S A (2013). Detailed Assessment of Global Cu Resource Trends and Endowments. Econ. Geol. 2013, 108, 1163–1183. https://doi.org/10.2113/econgeo.108.5.1163

Ni: personal communication BGR, Dr. M. Szurlies, Jan 2020; and Calvo G, Mudd G, Valero A, Valero A (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources. 5(4), 36; https://doi.org/10.3390/resources5040036

Cr: USGS 2015 minerals Yearbook. Chromium statistics https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/chromium/myb1-2015-chrom.pdf accessed July 2020

Sn: USGS Tin statistics information https://www.usgs.gov/centers/nmic/tin-statistics-and-information accessed July 2020; and Company information Cassiterite https://allseasonglobal.com/metals-minerals/mineral-ores/cassiterite/ accessed July 2020

Zn: Calvo G, Mudd G, Valero A, Valero A (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources. 5(4), 36; https://doi.org/10.3390/resources5040036

Sr: USGS Strontium statistics and information https://www.usgs.gov/centers/nmic/strontium-statistics-and-information ; and Company Website intercontinental Mining https://www.intercontinentalmining.com/strontium/ accessed July 2020

REE: Van Gosen BS, Verplanck PL, Seal RR, Long KR, and Gambog J (2017). Rare-earth elements, chap. O of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States— Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. O1– O31, https://doi.org/10.3133/pp1802O

W: Liedtke & Schmidt, 2014. Rohstoffrisikobewertung – Wolfram. DERA Rohstoffinformationen 19. 106 pages. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-19.pdf accessed July 2020

Mn: USGS Manganese statistics and information https://www.usgs.gov/centers/nmic/manganese-statistics-and-information and Manganese trading website https://tradingeconomics.com/commodity/manganese accessed July 2020

Ti: USGS Titanium statistics and information https://www.usgs.gov/centers/nmic/titanium-statistics-and-information accessed July 2020

Co: Al Barazi S (2018). Rohstoffrisikobewertung – Kobalt. DERA Rohstoffinformationen 36: 120 S.; Berlin. 978-3-943566-48-2. Access at https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-36.pdf accessed July 2020

Ta: Damm S (2018). Rohstoffrisikobewertung – Tantal – DERA Rohstoffinformationen 31: 82 S.; Berlin. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-31.pdf accessed July 2020 and

Schulz KJ, Piatak NM, and Papp JF (2017a). Niobium and Tantalum. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the United States - Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802M

Mo: USGS Molybdenum Statistics and Information https://www.usgs.gov/centers/nmic/molybdenum-statistics-and-information accessed July 2020

Zr: Mineral Zircon https://geology.com/minerals/zircon.shtml accessed July 2020

Au: Calvo G, Mudd G, Valero A, Valero A (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources. 5(4), 36; https://doi.org/10.3390/resources5040036

Ga: Liedtke M and Huy D (2018). Rohstoffrisikobewertung – Gallium. DERA Rohstoffinformationen 35: 86 S.; Berlin. ISBN: 978-3-943566-50-5. https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_gallium-2018.pdf? accessed Aug 2020

In: Schwarz-Schampera U (2014). Indium. Chapter 9 in Gunn (Ed). Critical Metals Handbook. John Wiley & Sons, Oxford. https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118755341.ch9

Pd: Schmidt M (2015). Rohstoffrisikobewertung – Platingruppenmetalle. DERA Rohstoffinformationen 26: 156 page. https://www.bgr.bund.de/DERA/DE/Downloads/studie_Platin_2015.html accessed Aug 2020

Sb: Schmidt M (2013). Rohstoffrisikobewertung – Antimon. DERA Rohstoffinformationen 18: 68 pages. https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-18.pdf? accessed Aug 2020

Ge: USGS Germanium Statistics and Information https://www.usgs.gov/centers/nmic/germanium-statistics-and-information accessed Aug 2020

V: USGS Vanadium Statistics and Information https://www.usgs.gov/centers/nmic/vanadium-statistics-and-information accessed Aug 2020

Ag: USGS Silver Minerals Yearbook 2016 USGS Vanadium Statistics and Information https://www.usgs.gov/centers/nmic/vanadium-statistics-and-information accessed July 2020; USGS Silver Statistics and Information https://www.usgs.gov/centers/nmic/silver-statistics-and-information accessed Aug 2020

Pb: Calvo G, Mudd G, Valero A, Valero A (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources. 5(4), 36; https://doi.org/10.3390/resources5040036

Nb: Schulz KJ, Piatak NM, and Papp JF (2017a). Niobium and Tantalum. In: Schulz KJ, DeYoung JH, Bradley DC, and Seal RR, II (2017). Critical mineral resources of the

United States - Economic and environmental geology and prospects for future supply: USGS Professional Paper 1802. https://doi.org/10.3133/pp1802M.

As: USGS Arsenic Statistics and Information https://www.usgs.gov/centers/nmic/arsenic-statistics-and-information accessed Aug 2020

Li: Schmidt M (2018). Rohstoffrisikobewertung – Lithium. DERA Rohstoffinformationen 33: 141 pages. https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_lithium_2017.pdf accessed Aug 2020

Pt: Schmidt M (2015). Rohstoffrisikobewertung – Platingruppenmetalle. DERA Rohstoffinformationen 26: 156 pages. https://www.bgr.bund.de/DERA/DE/Downloads/studie_Platin_2015.html accessed Aug 2020

Appendix IV: Metal value of Au, Cu, Pt, Pd in smartphones

Updated from **Figure 5.3**, with US $ to € calculated with monthly exchange rate