The Material Basis of ICT

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Abstract. Technologies for storing, transmitting, and processing information have made astounding progress in dematerialization. The amount of physical mass needed to represent one bit of information has dramatically decreased in the last few years, and is still declining. However, information will always need a material basis. In this chapter, we address both the upstream (from mining to the product) and the downstream (from the product to final disposal) implications of the composition of an average Swiss end-of-life (EoL) consumer ICT device from a materials perspective. Regarding the upstream implications, we calculate the scores of the MIPS material rucksack indicator and the ReCiPe mineral resource depletion indicator for selected materials contained in ICT devices, namely polymers, the base metals Al, Cu, and Fe, and the geochemically scarce metals Ag, Au, and Pd. For primary production of one kg of raw material found in consumer ICT devices, the highest material rucksack and resource depletion scores are obtained for the three scarce metals Ag, Au, and Pd; almost the entire material rucksack for these metals is determined by the mining and refining processes. This picture changes when indicator scores are scaled to their relative mass per kg average Swiss EoL consumer ICT device: the base metals Fe and in particular Cu now score much higher than the scarce metals for both indicators. Regarding the downstream implications, we determine the effects of a substitution of primary raw materials in ICT devices with secondary raw materials recovered from EoL consumer ICT devices on both indicator scores. According to our results, such a substitution leads to benefits which are highest for the base metals, followed by scarce metals. The recovery of secondary raw materials from EoL consumer ICT devices can significantly reduce the need for primary raw materials and subsequently the material rucksacks and related impacts. However, increased recycling is not a panacea: the current rapid growth of the materials stock in the technosphere necessitates continuous natural resource depletion, and recycling itself is ultimately limited by thermodynamics.

Keywords: ICT, Material Rucksack, Mineral Resource Depletion, Scarce Metals, Materials Recovery

1 Introduction

Technologies for storing, transmitting, and processing information have a material basis. Modern ICT is based on a multitude of hardware devices with specific, complex materials compositions. The average materials composition of a consumer ICT device at the end of its useful life (reference year: 2010) in Switzerland has the following characteristics: the majority of the mass of such a device consists of the base metals iron (Fe), aluminum (Al), and copper (Cu), polymers (mainly ABS, PC, PC/ABS, PE, PS, and SAN[1]) and glass [1-3] (see Figure 1). Besides the three base metals, consumer ICT devices also contain a large number of scarce metals,[2] including, among others, gold (Au), indium (In), platinum group metals (PGM) such as palladium (Pd) and platinum (Pt), rare earth elements (REE) such as dysprosium and neodymium, silver (Ag), and tantalum (Ta) (see Figure 1 for selected scarce metals occurring in consumer ICT devices). In the last few decades, an increasing number of elements represented in the periodic table has found its way into ICT [5], which requires devices for infrastructure (e.g., servers, routers, switches, base stations, and optical fiber cables) in addition to consumer devices.

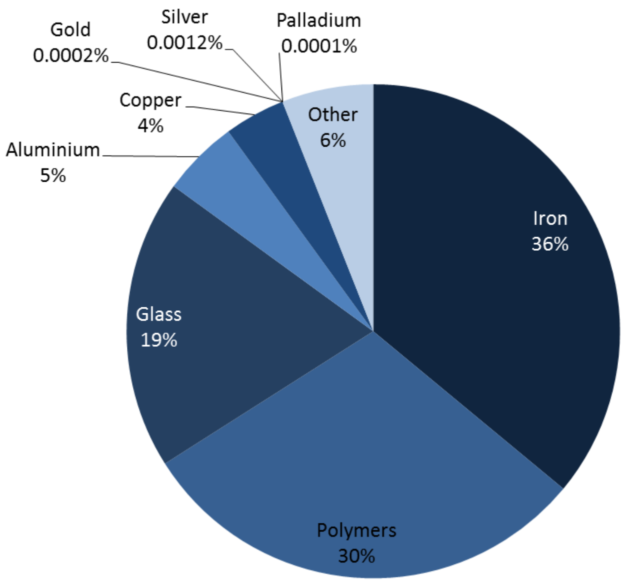

Fig. 1: Relative mass distribution of the materials contained in EoL consumer ICT devices in Switzerland (reference year: 2010) [3,1].

1 ABS: acrylonitrile butadiene styrene; PC: polycarbonate; PC/ABS: polycarbonate/acrylonitrile butadiene styrene blend; PE: polyethylene; PS: polystyrene; SAN: styrene acrylonitrile.

2 A metal is called geochemically scarce if it occurs at an average concentration below 0.01 weight percent in the earth's crust [4]. In this chapter, we use "scarce" as a synonym for "geochemically scarce."

However, the material composition of ICT devices (see Figure 1 for end-of-life consumer (EoL) ICT devices) tells only part of the story about the material basis of ICT. Both “upstream” processes (mining, refining, and production of the raw materials; production and assembly of the components; and the product itself) and “downstream” processes (product use, materials recovery, and final disposal) associated with an ICT device generate a multitude of material flows which are not obvious to its user [3,6,7].

In the following two sections, we will address up- and downstream implications of the average materials composition of EoL) consumer ICT devices (reference year: 2010) in Switzerland, focusing mainly on metals.

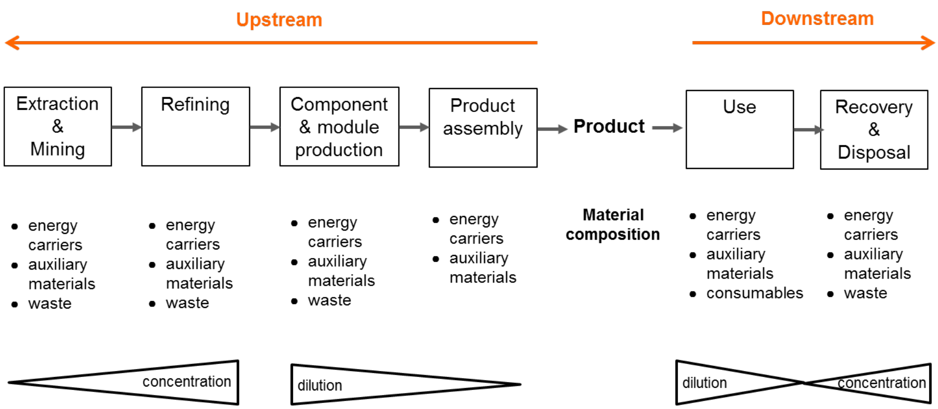

Fig. 2: Processes and material flows (focus: metals) contributing to the material basis of an ICT device, including the perspectives applied in this chapter (upstream and downstream) and metal concentration and dilution phases along the life cycle

2 Upstream Issues

2.1 ICT Raw Material Rucksacks

Each of the materials determining the composition of an average ICT device is associated with a material “rucksack” that includes all material flows connected to their extraction/mining, refining, incorporation into components and modules, and assembly of these components and modules to the final product. The calculation of the material rucksack requires data on the material and energy flows of all processes involved. Figure 3 shows the material rucksack per kg of selected raw materials found in ICT (polymers, the base metals Al, Co, and Fe, and the scarce metals Au, Ag, and Pd) as material input per unit of service (MIPS) scores [8].

In addition to these material rucksacks, Figure 3 also shows the implications for mineral resource depletion. Mineral resource depletion is one of the issues typically addressed in the ongoing discussion on supply risks of mineral raw materials, which have become a major issue due to emerging technologies’ increased demand for scarce metals [9]. The new concept of criticality, which seeks to capture both the raw material supply risks and the vulnerability of systems (e.g., companies, sectors, economies, societies) to a potential raw material supply disruption, emerged only some years ago [10,11]. The criticality concept has meanwhile been applied in several studies, showing that many scarce metals, among others gallium, germanium, indium, PGM, REE, or Ta, are to be considered "critical." Most of these studies address long-term geological availability, some of them including mineral deposit[3] information. The criticality study commissioned by the European Union [12], which is currently being updated, does not address geological availability because of the time horizon of the study (10 years) as well as reservations with regard to the use of concepts such as "reserve"[4], "reserve base"[5], "resource"[6] and the "static lifetime"[7] as indicators for geological availability.

In Figure 3, the implications for mineral resource depletion per kg of raw materials found in ICT are represented by the ReCiPe[8] life cycle assessment minerals resource depletion midpoint indicator (primary resources) [13]. This indicator monetizes the energy requirements of resource extraction, with the marginal increase of extraction cost per kg of extracted resource as a base for the model. Other mineral resource depletion indicators used in life cycle impact assessment calculate the ratio between use and deposits/reserves (CML method[9]), the surplus energy required for mining resources with a decreased ore grade at some point in the future (Eco-indicator method[10]), or exergy [16].

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3 A deposit is any accumulation of a mineral or a group of minerals that may be economically valuable [12].

4 A reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable [12].

5 The reserve base is the reserve of a resource plus those parts of the resource that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics [12].

6 A resource is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a mineral commodity [12].

7 The static lifetime is the ratio between reserve or reserve base and annual mine production [12].

8 The authors chose the acronym "ReCiPe" because the method is expected to provide a recipe for calculating life cycle impact category indicators and at the same time represent the initials of the institutes that were main contributors to this project [13].

9 The CML method is a problem-oriented impact assessment method developed at the Center of Environmental Science (CML) of Leiden University (NL) and described in their "operational guide to the ISO standards." [14]

10 The Eco-Indicator '99 method is an endpoint method that aggregates all impacts into three different damage categories (damage to human health, to ecosystem quality, and to the available resources). The method was developed in the Netherlands and is among the most often used life cycle impact assessment methods in Europe [15].

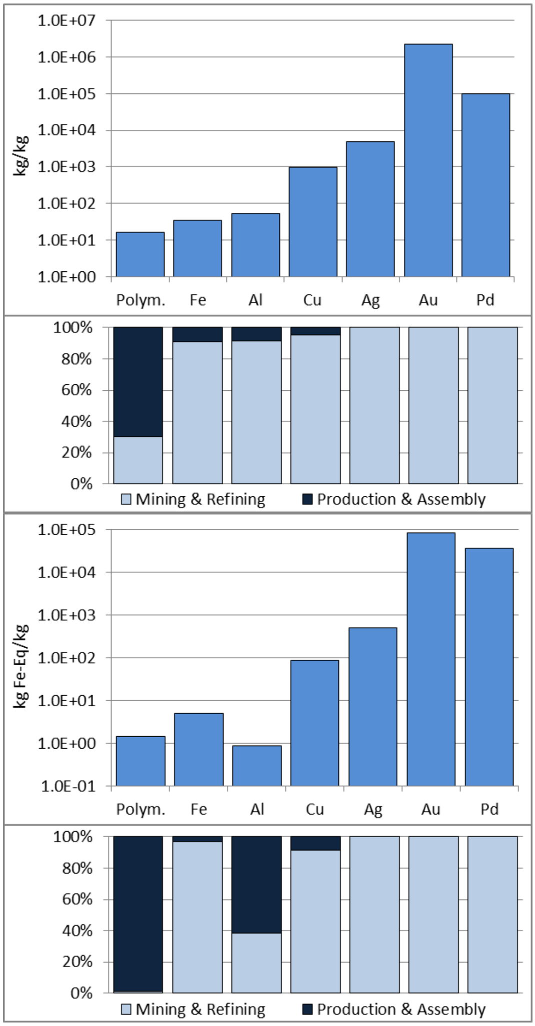

Fig. 3: Material rucksack and mineral resource depletion scores per kg of selected raw materials found in ICT. Upper left: MIPS scores in kg of total material input per kg of material. Lower left: corresponding shares of mining & refining and production & assembly. Upper right: ReCiPe mineral resource depletion (primary resources) scores in kg Fe equivalents per kg of material. Lower right: corresponding shares of mining & refining and production & assembly. Data source: ecoinvent v3.01 [17].

Both the MIPS score and the minerals resource depletion indicator in Figure 3 were calculated with ecoinvent v3.01 data, using the allocation-based attributional system model [17]. As shown in Figure 3, the material rucksacks per kg of raw materials found in ICT are significantly higher (by a factor of 1,000 to 10,000) for the scarce metals Ag, Au, and Pd than for the polymers and the base metals Al and Fe; Cu has a score that is closer to the three scarce metals than the two other base metals.

Almost the entire material rucksack for the scarce metals is determined by the mining and refining processes (i.e., the process of concentrating them into raw materials for production), while for all three base metals, the material rucksack is partly (5 to 10%) and for the polymers mainly (about 70%) determined by the production and assembly processes (i.e., dilution of the raw materials into products). Ag, Au, and Pd also score highest on the ReCiPe mineral resource depletion indicator. The difference between Au and Pd, the two materials with the highest scores for both indicators, is smaller for ReCiPe than for MIPS. Al has a higher MIPS score than Fe, but a lower ReCiPe score. Compared to the material rucksack indicator MIPS, the relative contribution of the production and assembly processes (i.e., dilution of raw materials into products) as expressed by ReCiPe is considerably larger for polymers and Al and smaller for Fe.

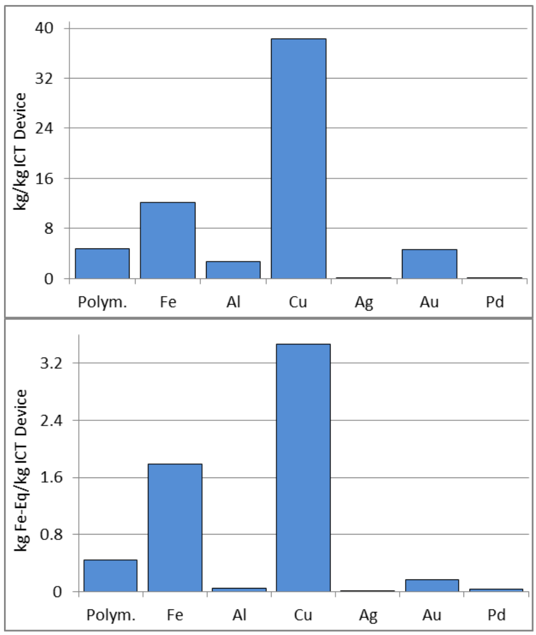

Fig. 4: Material rucksack and mineral resource depletion scores for selected raw materials, scaled to their relative mass in 1 kg average Swiss EoL consumer ICT device. Left: MIPS scores in kg total material input per kg ICT device. Right: ReCiPe mineral resource depletion (primary resources) scores in kg Fe equivalents per kg ICT device. Data source: ecoinvent v3.01 [17].

Figure 4 shows the scores for the same materials, however with indicators scaled to their relative mass per kg average EoL consumer ICT device. This provides a completely different picture than Figure 3 since the mass fractions of the materials in the device are orders of magnitude apart from each other. The material rucksack scores are now by far the highest for Cu, followed by Fe, polymers, and Au, while for the ReCiPe mineral resource depletion indicator, the scores are highest for the base metals Cu and Fe, followed by the polymers and Au.

3. Downstream Issues

3.1 Effects of Materials Recovery on Material Rucksacks and Resource Depletion

In this chapter, we do not consider energy carriers, auxiliary materials, and consumables required in the use phase, as our focus is on the implications of the material composition of a consumer ICT device. We therefore skip the use phase in our downstream perspective and address the effects of materials recovery from EoL consumer ICT devices. In particular, we elaborate on the effects of a substitution of primary raw materials with secondary raw materials recovered from EoL consumer ICT devices on MIPS and ReCiPe mineral resource depletion indicator scores, assuming that the recovered materials are used solely for the production of new ICT devices. Two recovery rates are considered: rates currently achieved in Switzerland and technically achievable rates. Concerning the recovery of plastics, it has to be considered that their recycling potential is limited by brominated flame retardants and other problematic additives [18]; when recycling metals, significant quality and dilution losses might occur [19,20]. The effects of recycling are calculated as the difference between the scores resulting from recycling activities and the (avoided) scores from primary production of the material replaced by recycling. In the case of substitution of primary copper by copper recovered from EoL consumer ICT devices, the scores obtained for the process "Copper market for primary production only" are subtracted from the scores calculated for the process "Metal part of electronics scrap, in blister copper | treatment of, by electrolytic refining."

As shown in Figure 5, the recovery of selected raw materials results in a reduction of the material rucksack and resource depletion indicator scores shown in Figure 4. The environmental benefits are greatest for the base metals, with estimated current recovery rates of 90% for Fe and 85% for Al and Cu, followed by scarce metals, with 80% for Ag, Au, and Pd, and finally polymers with 40% [21]. Assuming technically achievable recovery rates of 70% for plastics, 88% for Ag, Au, and Pd as well as 95% for Fe, Al, and Cu [21], the improvement potentials are highest for polymers with regard to the material rucksack indicator, followed by Cu for both indicators, and Al, again with regard to the materials rucksack indicator.

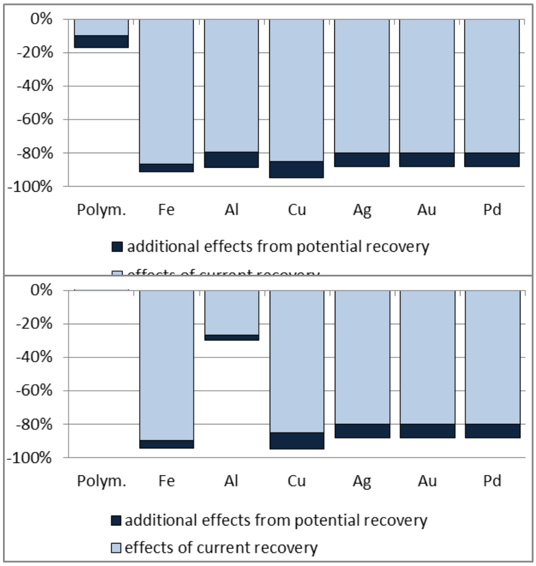

Fig. 5: Effects of the substitution of primary raw materials in ICT devices with secondary raw materials recovered from EoL consumer ICT devices on material rucksack and mineral resource depletion scores with current and potential (technically achievable) recovery rates. Left: Reduction of MIPS scores relative to primary production. Right: Reduction of ReCiPe mineral resource depletion indicator scores relative to primary production. 100% corresponds to the scores reported in Figure 4.

3.2 Scarce Metals Recovery

Despite the concentrations of scarce metals in EoL devices typically being much lower than those of the base metals Al, Cu, and Fe, post-disassembly concentrations can be considered high compared to minimum profitable ore grades [5]. Yet recovery rates of several scarce metals, such as gallium, germanium, indium, REE, and Ta from EoL products have been shown to lie below 1%, while the recovery rates for "precious" scarce metals such as Ag, Au, Pd or Pt exceed 50% [22].

Scarce metal recovery rates are a function of the efficiencies of the processes determining the recycling chain, i.e., collection, pre-processing, and end-processing [23].

Collection efficiency for waste electrical and electronic equipment (WEEE) depends on how well the collection systems in place are adapted to the habits of the owners of the EoL product to be collected and how well they are informed about the collection systems. The *efficiency of pre-processing* depends on the specific implementation and combination of the different steps involved, namely sorting, dismantling, and physical and chemical separation. In order to optimize their costs, recyclers in countries such as Switzerland increasingly pre-process WEEE with automatized, mechanical processes, manual dismantling being limited to separating hazardous materials and disturbing materials before mechanical processing. However, this may lead to mixing materials in a way that negatively affects the recovery rates of certain materials. For example, scarce metals may end up in fine plastic fractions sent to energy recovery processes, resulting in dissipation[11] of the metals [24,25]. Several projects are currently investigating options to better exploit the potential of manual dismantling of WEEE in view of higher scarce metals recovery rates, including concepts aiming at integrating "best" pre-processing in developing countries and "best" end-processing in international state-of-the-art end-processing facilities ("best-of-two-worlds approach") [26-30]. Other projects aim at optimizing the allocation of output fractions from pre-processing to end-processing [31]. It should be kept in mind for all of them that end-processing is ultimately limited by thermodynamics, which is why certain metal combinations cannot be successfully recycled [20,32]. Accordingly, not only the actors determining the design of the collection, pre-processing, and end-processing systems will have to take their responsibilities seriously to increase scarce metals recovery, but also product designers.

4. Conclusion and Outlook

ICT is driving the rapid expansion of the material substrate contained in countless devices in use, in terms of both absolute volumes and number of elements, specifically scarce metals. This requires an accelerating intake of primary raw materials, mainly minerals from the lithosphere, which is coupled with rapidly growing material rucksacks. The recovery of secondary raw materials from EoL devices can significantly reduce the need for primary raw materials and subsequently the material rucksacks and mineral resource depletion. However, increased recycling is not a panacea:

- The materials stock in the technosphere is growing rapidly, which entails continuing natural resource depletion. For substitution of primary resources by secondary raw materials to become relevant, steady state conditions have to be reached.
- The recovery rates of the majority of the elements, in particular scarce metals, are very low. Some may be increased considerably, but many cannot, due to thermodynamic limits in the established metallurgic processes of metal refining. Hence, considerable leakage from the envisioned "closed-loop economy" and dissipation to the environment seem unavoidable.
- In a closed loop economy, faster materials turnover due to e.g. shorter residence times of ICT devices leads to increased material losses into inaccessible stocks. Primary raw materials are required to compensate for these losses.
- The material rucksacks for raw materials production tend to increase with decreasing ore grades, which most of the remaining deposits and mineral mines are facing.

[11] "Dissipation" – in this context – refers to the dilution of a material in the technosphere or ecosphere in such a way that its recovery is made practically impossible. The "technosphere" includes all objects and associated material flows that have been created by humankind and are under its control [9].

- Not only are the primary ore grades decreasing, but the secondary deposits are also becoming less accessible as a result of continued miniaturiation, augmenting substrate complexity, and a forceful trend towards “pervasive computing” [33].
- Some of the materials are being phased out from ICT, in particular some toxic heavy metals such as Hg, Pb, and Cd. For example, under the recent UN Minamata Convention on Mercury [34], Hg must no longer be recycled in the technosphere. Therefore, disposal facilities that provide long-term safety are needed, which may require new financing mechanisms.

In view of these perspectives, we draw the following conclusions:

- In the short term, recycling rates should be systematically maximized for the specific elements contained in ICT devices, not just for their total mass. The material turnover in a leaking loop economy needs to be slowed down, i.e., active residence time has to be maximized.
- In the medium term, raw materials production, ICT devices as well as recycling processes have to be designed to achieve minimal material dissipation and minimal material rucksacks.
- In the long term, the material substrates of ICT (as well as all other technologies) need to be changed toward the use of more abundant elements and bio-compatible substances.

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