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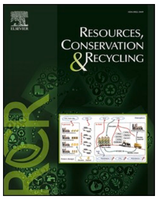

Full length article

Unlocking the potential of e-waste: A material quantification analysis of Cu, Cr, In, Mg, Nb, and Nd in the EU

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ABSTRACT

Waste electronics present a growing concern due to their economic value and material intensification, making proper collection and recycling essential for sustainable growth. However, quantifying the size and composition of waste flows is challenging. Using a material flow analysis this study combines electronic waste flows and product compositions of six selected elements (chromium, copper, indium, magnesium, neodymium, and niobium) based on their significance in the electrical and electronic products (EEE) in the EU. The study found that in 2018, 52 % of all WEEE generated in EU28+3 was properly collected and recycled, and the remaining 48 % were unreported or unaccounted for of which the selected elements represented 5 %, representing a combined loss of €1.41 billion. The obtained results provide a much-needed perspective to map electronic products on a material level for circular material supply. Proper collection and recycling of WEEE are crucial for sustainable growth and the recovery of valuable materials.

1. Introduction

According to the OECD, global material use is projected to more than double from 79 Gt in 2011 to 167 Gt in 2060. The past decade has seen a surge in resource pressure and demand driven by population growth, technological advancements, industrialization and transition towards clean energy (Oberle et al., 2019). This increased the demand of materials and attention from global authorities towards resource efficiency and circular economy strategies (British Geological Survey et al., 2017a; 2017b; European Commission, 2008a; Henderson, 2013).

To address these challenges, the european commission (EC) launched the "Raw Materials Initiative" in 2008, aimed at ensuring consistent and unhindered sources of raw materials while also addressing resource scarcity (European Commission, 2008b, 2008a). In 2011, the EC identified 14 critical raw materials (CRMs) that require special attention due to their economic importance and higher risk of supply interruption. The EC's definition of CRMs encompasses materials or elements in scarce supply that are vital for sustainable economic development. This list has been updated every three years since 2011 to reflect technological advancements (British Geological Survey et al., 2017a; European Commission, 2011; Grohol and Veeh, 2023; Nilsson et al., 2009). The 2023 update introduces 34 CRMs, encompassing heavy and light rare earth elements (REE), platinum-group metals, as well as newly added strategic materials: arsenic, feldspar, helium, manganese, copper, and nickel. (Grohol and Veeh, 2023). Despite having one of the world's largest economies, the EU relies heavily on imported raw materials (e.g. Cr, Cu, In, Mg and Nb) (European Commission and Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2021). The EU's pursuit of climate neutrality and a circular economy hinges on responsibly and sustainably sourcing materials (Bobba et al., 2020a). Securing sustainable access and supply of raw materials through circular economy, is vital for the european union (EU) economy as it increases value chains resilience and ensures supply stability (Bobba et al., 2020b, 2018; OECD, 2015). Import dependency exposes the EU to substantial economic and supply risks, especially in manufacturing, where trade limitations and disruptions can affect material supply and pricing.

In Europe, hazardous materials are regulated by several laws and directives enforced by the EU Member States (MS) with the support of the european chemicals agency (ECHA). ECHA, an EU agency, provides scientific and technical expertise in chemical safety and manages the registration, evaluation, authorisation, restriction, classification, labelling, and communication of hazardous substances under REACH (registration, evaluation, authorisation and restriction of chemicals), CLP (classification, labelling and packaging), BPR (biocidal products

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regulation) etc. ECHA, defines hazardous materials as substances or mixtures bearing physical, health and/or environmental risks (European Chemicals Agency (ECHA), 2023).

The electronic industry has become an integral driver for our modern lifestyle and plays a crucial role in our society. Fast product design cycles and unsustainable consumer habits present challenges (i.e. inappropriate treatment or disposal of products containing hazardous materials), opportunities (recovery of valuable material) and add further demand for materials (Forti et al., 2020; Wagner et al., 2021). This sector is vulnerable as it relies heavily on these materials. Lack of access could impede the EU's electronics industry in meeting rising demand (Bobba et al., 2018; European Commission, 2008b).

Urban mining reclaims compounds, materials, and elements from anthropogenic sources, including waste electrical and electronic equipment (WEEE), being a crucial source for recovering of materials. Urban mining diversifies resource supply, reduces import dependence, minimizing depletion, and securing sustainable sources (European Commission, 2019; Huisman et al., 2017a; Johansson et al., 2013). To develop a sustainable approach for secondary resources use, extraction and recovery, comprehending material content, product quantity, and end-of-life equipment is crucial (Wagner et al., 2021). By mapping and quantifying these flows, we can develop long-term strategies to mitigate supply disruptions. Appendices (A.) A.1 and A.2 illustrate the CRM relevant chemical elements for manufacturing and upgrading electrical and electronic equipment (EEE) considering their hazardousness under the European Chemical Agency (European Chemicals Agency (ECHA), 2022; Huisman et al., 2017a).

This study extends the temporal dimension and bridges a knowledge gap of the selected materials flow within EEE. Previous research, as noted in the literature, has predominantly focused on limited geographic scopes (Parajuly et al., 2017; Van Eygen et al., 2016; Vexler et al., 2004), selected classifications (Dimitrakakis et al., 2009; Johnson et al., 2018; Karlsson, 2021; Salhofer et al., 2011) and a narrow range of metals (Chancerel and Rotter, 2009; Habib et al., 2022; Horta Arduin et al., 2020; Van Eygen et al., 2016; Vexler et al., 2004). This research extends from 2000 to 2018, offering an overview of the selected materials in various (W)EEE flows across all EU28+3 countries, thereby providing a more holistic understanding of the dynamics within this domain. This extended time dimension allows us to capture critical trends and shifts over nearly two decades (Huisman et al., 2017a; Mählitz et al., 2020; Mining, 2015; Van Eygen et al., 2016). Furthermore, our research methodology builds upon well-established methodologies (Balde et al., 2015; Bobba et al., 2018, 2020b, 2020a; Huisman et al., 2015, 2017a, 2017b; Huisman and Baldé, 2013; Wagner et al., 2021) used by the EC to estimate flows as well as EEE composition which incorporates the urban mine platform and Wagner et al., 2021 as a key reference point (Hischier et al., 2007; Huisman, 2004, 2003; Huisman et al., 2012; Magalini et al., 2014b; Oguchi, 2007). By adopting their approach, we conduct material flow characterization, ensuring continuity in the research landscape.

In this work, we provide insight into the flows of six selected materials in the EEE sector in the EU: copper (Cu), chromium (Cr), magnesium (Mg), indium (In), niobium (Nb), and neodymium (Nd). These elements were chosen due to their significance in the sector, including supply risk, economic importance, and hazardousness (see A.1 - A.4) (Duarte et al., 2010; European Chemical Agency, 2021a; European Chemical Agency (ECHA), 2021a, 2021b; European Chemicals Agency (ECHA), 2021a, 2021b, 2021c; Nnorom and Osibanjo, 2009; Townsend, 2011).

In the EU, In, Mg and Nb are considered CRM due to their supply risk and economic importance (European Commission, 2020). In is characterized by its high thermal and electrical conductivity, and resistance to thermal fatigue, which makes it suitable for use in electronic applications such as photovoltaic (PV) panels, flat panel displays, alloys (Bobba et al., 2020b) and semiconductors (U.S. Geological Survey, 2019). Nb is mainly used in magnets, lamps, and IT equipment (Schulz et al., 2017), while Mg is valued for its lightweight, heat and oxidation resistance as well as relatively high tensile strength making it an ideal material for the automotive, aerospace and electronics industry (Shapiro, 1999; U.S. Geological Survey, 2019). Nd is a REE with malleable characteristics used in the manufacturing of magnets, and various household equipment such as washing machines, desktops and laptops (Crock, 2016; Thornton et al., 1969). Cr is a tough and brittle transition metal, highly corrosion-resistant and a primary additive in stainless steel production. It holds a key role in electronics, particularly in cooling, freezing, and larger equipment, forming stainless steel component (Steinitz, 1986). Despite Cr not currently considered a CRM, in 2018 the US Department of the Interior added Cr to its list of 35 critical minerals (83 FR 23,295) highlighting its importance for US industry and defence applications (Blengini et al., 2020; Goonan, 2011). Cu, a malleable and ductile base metal, is widely used in various industries, including EEE production, transportation, and construction, due to its excellent thermal and electrical conductivity (Goonan, 2011).

The study presents and analyses 1) quantification of selected materials in EEE over time (2010–2018) as per EU6 collection categories (as described in WEEE Directive 2012/19/EU, see A.2 and A.5) 2) quantification in various flows: EEE Placed on the Market (POM), stocks, waste generated, officially collected and reported and unreported and unaccounted flows in the EU28+3 (the MS plus Norway, Great Britan and Switzerland (European Commission, 2012a).

2. Materials and methods

2.1. System boundary of this research

This research examines the material flows of six elements – Cr, Cu, In, Mg, Nb and Nd - within EEE and WEEE across the EU28+3 region spanning 2010 to 2018, with a specific focus on the year 2018. Fig. 1 flow diagram serves as the foundation, illustrating the selected elements flow within the EU28+3 region for 2018. This year is chosen as reference as its the latest year with official information from EU MS to the EC following Article 16 of the WEEE Directive 2012/19/EU (European Commission, 2012b).

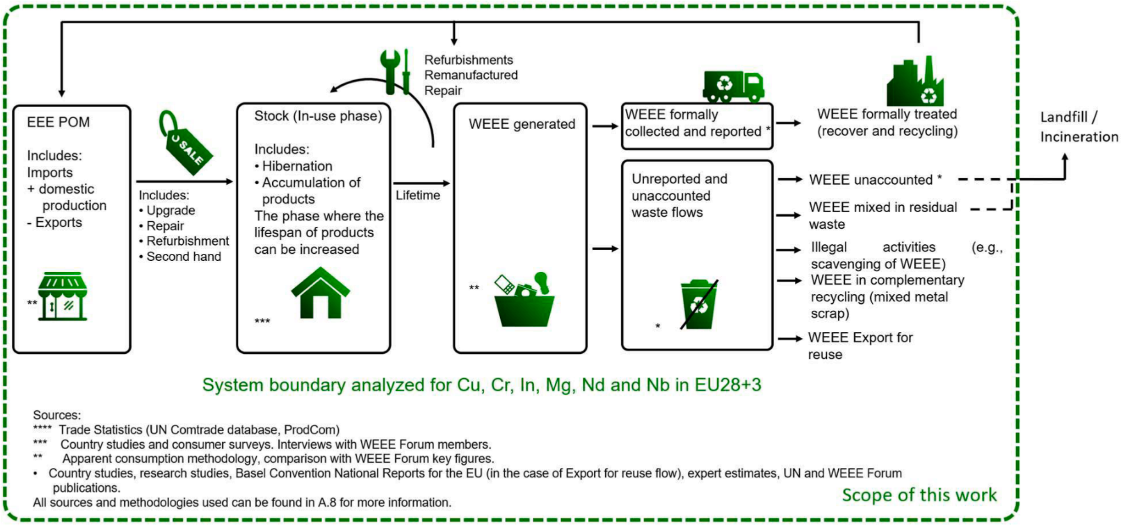
The analysed (W)EEE flows (Fig. 1) include 1) products POM including imports, domestic production, refurbished/repaired products and exports 2) Stock comprises products in use, hibernation and accumulated 3) WEEE generated 4) WEEE formally collected and reported and unreported flows. These are aligned with the EU's Waste Statistics Regulation and the WEEE Directive 2002/96/EC and 2012/19/EU (Eunomia Research and Consulting Ltd, 2018; European Commission, 2013, 2012b, 2003)). Furthermore, our studies results are illustrated per the amended WEEE Directive 2012/19/EU collection categories (EU6, see A.5). In this work, the EU6 collection category VI (Information and Telecommunication, IT Equipment) is used as an example.

2.2. Methodology and data sources to quantify WEEE flows

All data analysis employed the EU6 collection category, with conversions carried out using the UNU Keys and their correlated relationships with the WEEE Directive collection categories (refer to A.6).

In April 2017 a new EC regulation (EU) 2017/699 standarized methodologies for calculating EEE POM weights and WEEE generation across EU MS (European Commission, 2017a, p. 699). The Multivariate Sales-Stock-Lifespan method (Implementing Act of Article 7 of the EU-WEEE Directive) was used to determine EEE stock and flows (Magalini et al., 2014a). The market input component is determined through "Apparent Consumption" methodology which uses official statistical data as the central data source, encompassing domestic production figures extracted from the ProdCom statistics and EEE products that are subtracted from the exports and imports (Balde et al., 2015).

As a first step, the WEEE POM information over time (EEE POM(t)) was estimated using relevant combined nomenclature (CN) codes



Sources:
**** Trade Statistics (UN Comtrade database, ProdCom)
*** Country studies and consumer surveys. Interviews with WEEE Forum members.
** Apparent consumption methodology, comparison with WEEE Forum key figures.
- Country studies, research studies, Basel Convention National Reports for the EU (in the case of Export for reuse flow), expert estimates, UN and WEEE Forum publications.

All sources and methodologies used can be found in A.8 for more information.

Fig. 1. Research system boundary adapted from (Baldé et al., 2020; Habib et al., 2022; Shittu et al., 2022). All flow definitions and data sources can be found in A.8.

(Balde et al., 2015; European Commission, 2017b; Forti et al., 2018; Goonan, 2011; Habib et al., 2022). CN codes, integral for EU export certificates, can be cross-referenced with ProdCom codes via Eurostat correspondence tables (Balde et al., 2015; European Commission and Eurostat, 2022). ProdCom codes provide national-level manufacturing statistics within EU reporting countries (European Commission and Eurostat, 2022). These estimations were later compared with WEEE Forum Key figures, ensuring reliable and coherent time series of validated POM data from EU countries (WEEE Forum, 2019).

$$EEE\ POM(t) = Domestic\ Production + Import - Export \tag{1}$$

Subsequently, WEEE generated volumes were calculated using a POM sales-lifespan approach, incorporating lifespan parameters according to Commission Implementing Regulation (EU) 2017/699 (Balde et al., 2015; European Commission, 2017a). This involves using Eq. (2) to calculate WEEE for a given year (Balde et al., 2015; European Commission, 2017a; Forti et al., 2018; Habib et al., 2022).

$$WG\ (n) = \sum_{t=t0}^{n} EEE\ POM\ (t) * L^{(p)}\ (t, n) \tag{2}$$

WG(n) is the WEEE generated volume in year *n; POM(t)* is the POM product sales within historical years *t* before year *n; t0* is the initial year of products sales and the Weibull distribution $L^{(p)}(t, n)$ is the discard-based life-time profile for the batch of products sold in historical year t. This lifespan distribution reflects the probability of batch disposal over time, aligning the definition of waste as outlined in article 3 of the Waste Framework Directive (European Commission, 2012a; Forti et al., 2018; Habib et al., 2022).

$$L^{(p)}\ (t, n) = \frac{\propto(t)}{\beta\ (t)^{\propto(t)}}\ (n-t)^{\propto(t)-1}\ e^{-\left[\frac{n-t}{\beta(t)}\right]^{\alpha(t)}} \tag{3}$$

Lifespans for various UNU keys were taken from previous UNU country studies performed by (Forti et al., 2018). The average lifespans and weights for 2014 are illustrated in A.7 (Forti et al., 2018). With a classification of 54 categories, the detailed UNU keys' product classification and its alignment with the recast 2012/19/EU WEEE Directives are outlined in A.6 (Forti et al., 2018).

As a third step, the stock *S(n)* was estimated using the Apparent Consumption Methodology by summing all historical POM, *POM(t)* and subtracting the cumulative WEEE generated in those years *WG(n)*, where *n* is the evolution year and *t0* is the initial year that a product was sold (Forti et al., 2018).

$$S(n) = \sum_{t=t0}^{n} POM(t) - \sum_{t=t0}^{n} WG\ (n) \tag{4}$$

The analysis of WEEE officially collected and reported[1] (*WOCR*) was conducted using data from national registers across EU MS as reported to the EC and accessible in Eurostat for the latest available year (2018) (Forti et al., 2018). For Switzerland, 2018 information was accessed from SENS and SWICO technical reports, which are annually published (Baldé et al., 2020; Conte et al., 2020).

Unreported flows, illustrated in Fig. 1, include illegal activities (e.g. scavenging practices of WEEE), WEEE mixed within residual waste and WEEE export for reuse, also known as "complementary flows". EU MS do not report this type of flow to the EC, resulting in exceedingly limited, scattered, non-harmonized, and occasionally incomplete data. To assess these flows, sources from various projects, such as the urban mine platform, (Huisman et al., 2017a) CWIT project outcomes (Huisman et al., 2015), reviews of the in-depth review of the WEEE collection rates and targets in the EU (Baldé et al., 2020), country studies (Aurez et al., 2018; Mihai et al., 2019; Stowell et al., 2019) and various other publications, see A.8. For estimating the complementary recycling (mixed metal scrap) flow, a combination of Eurostat data and country studies was employed due to the non-uniform and occasionally incomplete methodologies utilized across Member States (European Commission and Eurostat, 2022).

Subsequently, the unaccounted flow[2] was estimated by subtracting the estimated WEEE generated (*WG*) and the *WOCR* from data derived from sources including SENS, Eurostat information for EU28+3, and pertinent country studies for corresponding years (A.8) using the following equation (Conte et al., 2020; Huisman et al., 2017a):

$$Unaccounted\ flows = WG - WOCR - \sum_{t=t0}^{n} unrepoted\ flows \tag{5}$$

2.3. Methodology and data sources to quantify material composition in WEEE flows

Product composition information was extracted from the urban mine platform (Huisman et al., 2017a) using the methodology described in Wagner et al. (Wagner et al., 2021). EEE product and component composition flow information were estimated by extracting EEE product

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[1] In some literature also known as WEEE collected

[2] In some literature also known as "the Gap" or "unknown whereabouts".

composition information from 2010 to 2018 through the urban mine platform applying the methods established therein (Huisman et al., 2017a; Wagner et al., 2021). Specifically, the EEE product compositions of the selected elements for all UNU Keys were multiplied with the tonnage of various total flows (POM-Eq. (1), WEEE generated-Eq. (2)-3, stock-Eq. (4), unreported and unaccounted flows-Eq. (5)) for a specific reference year (Huisman et al., 2017a). Initially, all flows were estimated at a UNU key level to enhance robustness, followed by conversion to the EU6 collection category using a correlation table (A.8).

$$emc\ UNU\ Key_y \text{ in } Flow_x = emc_{x\text{content}}\ \tfrac{\text{mg}}{\text{kg}} * \frac{Flow_{x\ (t)} \text{ of } UNU\ Key_y \text{ for the } Year_n}{1,000,000} \tag{6}$$

emc represents the element (*e)*, material (*m)* and component (*c*) of a specific UNU Key for a specific flow *x,* i.e. POM, stock, complementary and unreported flows. In this case, only the concentration (in%) of *emc* for a specific UNU Key *y* is known, it is multiplied by the flow (Eq. (6)). Similar to the calculation of WEEE, the estimated *emc* waste generated lifespan parameters a POM sales-lifespan approach is used. For a specific year *n*, the *emc* waste is the sum of the *emc* of the discarded product POM and multiply by the UNU Keys lifespan.

$$emc\ WG \Big/ UNU\ Key_y(n) = \sum_{t=t0}^{n} POM\ (t) * L^{(p)}\ (t, n) \tag{7}$$

A summary table of data sources and methodologies used for each (W)EEE flow can be found in A.8.

Assessing the quality and uncertainty of data is essential for ensuring the robustness and reliability of our study's findings. In this regard, we implemented the methodologies described in Wolk-Lewanowicz et al., Habib et al. and Wagner et al. and applied in the urbanmine platform (Habib et al., 2022; Huisman et al., 2017a; Wagner et al., 2021; Wolk-Lewanowicz et al., 2016). This involved quantifying and averaging the uncertainty and data quality for all (W)EEE flows and composition applying the ranges provided in A.9 on a case-by-case basis. For detailed information on the data quality characterization please refer to A.9.

3. Results and discussion

In this study, we focus on the mapping of Cr, Cu, In, Mg, Nb and Nd in category VI - IT Equipment (other EU6 WEEE collection categories are illustrated in A.10–14) within the scope defined in Fig. 1 (European Commission, 2012b). The result of the analysis of (W)EEE product flows can be found in A.15. To assess the significance of the selected materials, a comprehensive analysis was performed at both the product and component levels within the EU6 collection categories (see A.16 for the products with highest concentrations for the selected materials). By applying the methodologies described in Section 2, it is possible to quantify elements, materials and components found in (W)EEE in different types of flows in scope for all EU6 collection categories for EU28+3 and per country. This methodology allows not only to measure the share of different materials and components in different flows but illustrates the volume of secondary raw materials (SRM) available in the urban mine and the potential volume that could be recovered at country and regional levels.

3.1. Quantification of selected elements from 2010 to 2018

Trends in the changes of material composition over time, illustrated in Fig. 2 for EU 28+3 from 2010 to 2018, provide insights into technology development (e.g. continuous miniaturization of microchips), disruptions (e.g. replacement of cathode ray tubes by LED technology), legislation changes (e.g. banning of Pb-base soldering material), and enable forecast of future material composition which will allow stakeholders to make strategic decisions.

Fig. 2 illustrates that the stock amount for the selected elements is significantly higher than the POM and WEEE generated flows. This is mainly due to equipment being in an in-use phase and consumer behaviour practices such as hibernating (Shittu et al., 2022). Between 2010 and 2018, Nb demand decreased from 0.24 to 0.20 tonnes, while other selected materials remained stable in POM, stock, and WEEE flows. In IT equipment, Nb is mainly found in PCBs of computers and electrolytic capacitors (Montero et al., 2012). However, due to the trend of miniaturization in IT products, which makes them more energy-efficient and faster, consumers have been upgrading their devices. This has resulted in a decrease in Nb within POM and stock flows (Maurice et al., 2021; Ueberschaar et al., 2017). Nb's economic significance and reduced content in IT products are seen as a positive trend, mitigating its supply risk and potentially averting EU shortages (Blengini et al., 2020).

On the contrary, Cu stock volumes increased steadily from 108,435 tonnes in 2010 to 120,050 tonnes in 2018, as well as an increase in demand from 18,733 to 25,560 tonnes over the same period. This growth is attributed to the diversification of new products and primary contributor to components such as cables, PCBs, and magnets in IT equipment (Wilburn et al., 2001; Zhang et al., 2014). Its presence in IT

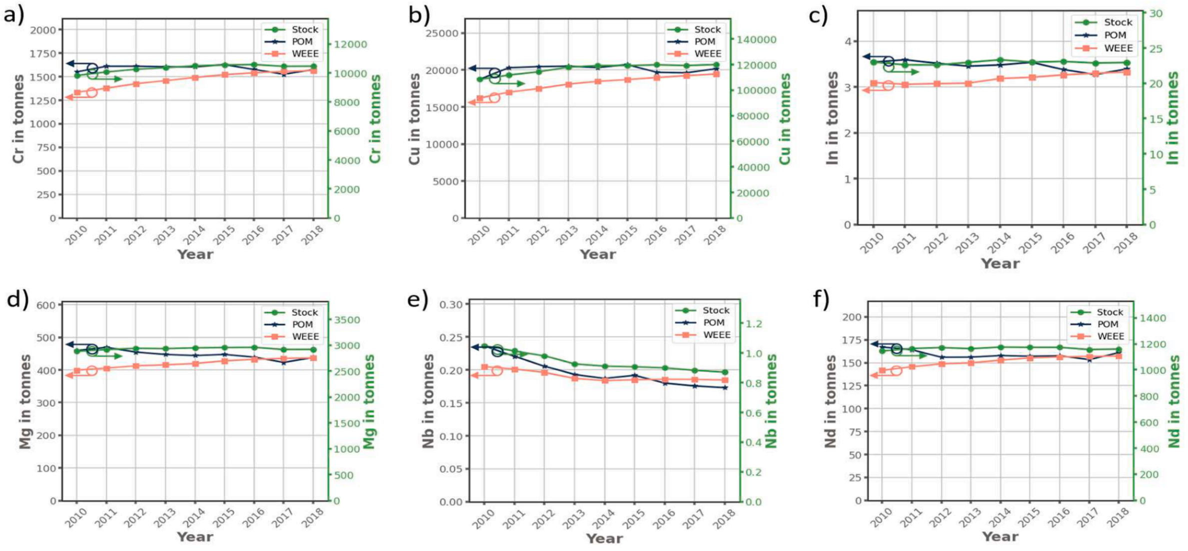


Fig. 2. POM, Stock and WEEE of (a) Cr, (b) Cu, (c) Mg, (d) Nd, (e) Nb (f) In contained in category VI – IT equipment in EU 28+3 from 2010 to 2018.

products surpasses that of other materials, underscoring its economic significance (Blengini et al., 2020). As a result the European Commission has defined it as a strategic raw material due to its growing demand in electric vehicles, renewable energy technologies (reaching 20 Mt in 2020), and other applications. This surge in demand could further stress global supply chains and potentially result in disruptions (Grohol and Veeh, 2023).

The demand of Cr has increased from 1549 tonnes in 2010 to 1980 tonnes in 2018. Its application is primarily linked to its unique physical properties, particularly its use as a coating in PCBs and magnets due to its diamagnetic characteristics (Bongers et al., 1968). Cr substantial presence in IT devices and various applications is economically crucial. However, its moderate supply risk, exacerbated by limited availability, raises potential concern. As per 2022 statistics, most of the global Cr supply originates from South Africa, Turkey, Kazakhstan, India, and Finland. While Cr(0) and Cr(III) are considered non-toxic, Cr(VI) is both carcinogenic and toxic ("Chromium Market Size, Share and Outlook Report, 2020–2025," 2020; Schulte, 2021, 2021). In IT devices, particularly older electronics, Cr(VI) can be present in specific components or coatings, and it may leach over time due to environmental factors like moisture, heat, or corrosives. In addition, CrO_3 is mainly used in industrial plating, anodic coating, and re-packaging processes (A.2) (European Chemical Agency, 2021a, 2021b). To address health and environmental concerns related to Cr(VI) and CrO_3, the EU has implemented regulations and standards aimed at reducing their usage and encouraging manufacturers to adopt safer alternatives.

Nd, found in computer hard disk drives (HDDs), magnets, and PCBs amongst others (Huisman et al., 2017a). Based on literature review and as illustrated in Fig. 2, Nd exhibited relatively stable quantities, ranging from 167 to 161 tonnes between 2010 and 2018, a phenomenon attributed to market penetration and component miniaturization (München et al., 2021). Beyond its significance in IT devices, Nd plays a crucial role in sustainable energy generation, electromobility, and electric motors (Crock, 2016; van Nielen et al., 2023). China dominance in producing over 70 % of the world's Nd supply creates supply risk due to the concentration of production and driving increased demand for recycling (American Chemical Society, 2020; Haxel, 2002; van Nielen et al., 2023).

In, commonly found in all IT equipment, particularly in LED screens and III-V semiconductors on printed circuit boards (PCBs) (Schuyler Anderson, 2021) exhibits usage patterns influence by technological advancements and sales trends (Huisman et al., 2017a). From 2010 (3.5 tonnes) to 2018 (3.4 tonnes), the demand for Indium and its waste generation (both at 0.003 tonnes for both years) remained relatively stable. According to Gómez et al. the electronics and photovoltaic industries are expected to drive In demand, requiring approximately 10.5 kt for EEE production from 2010 to 2050 (Gómez et al., 2023). In faces increased supply risk due to its rarity and production outside of the EU (Werner et al., 2015). While generally considered low in toxicity, III-V semiconductors containing indium arsenide, indium gallium arsenide or indium phosphide, exhibit toxicity in animals, have a high carcinogenic potential and can contaminate the environment when landfilled (Cui and Zhang, 2008; Tanaka, 2004).

Mg's physical and chemical properties making it a sought-after component in IT equipment, including capacitors, LEDs, and PCBs. Nevertheless, its demand has decreased from 459 in 2010 to 437 tonnes in 2018, a trend attributed to miniaturization. a trend attributed to miniaturization. Mg faces a low supply risk, thanks to its wide distribution in the Earth's crust and its non-hazardous nature (Lee Bray, 2021). Recovery and recycling of Mg is vital to reduce supply risk (Swain and Lee, 2019).

This methodology allows not only the analysis of different flows in

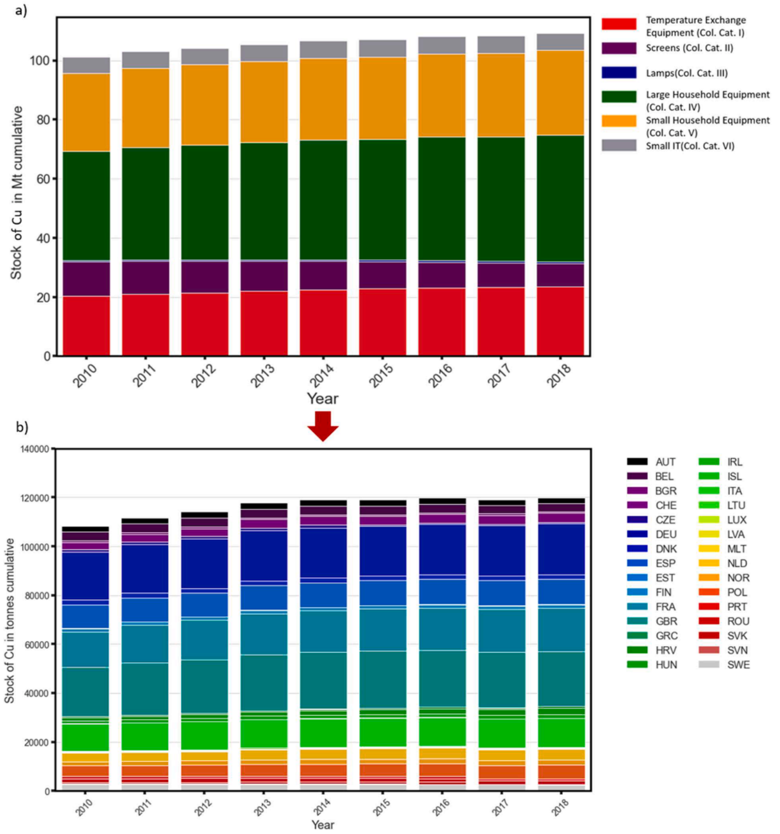


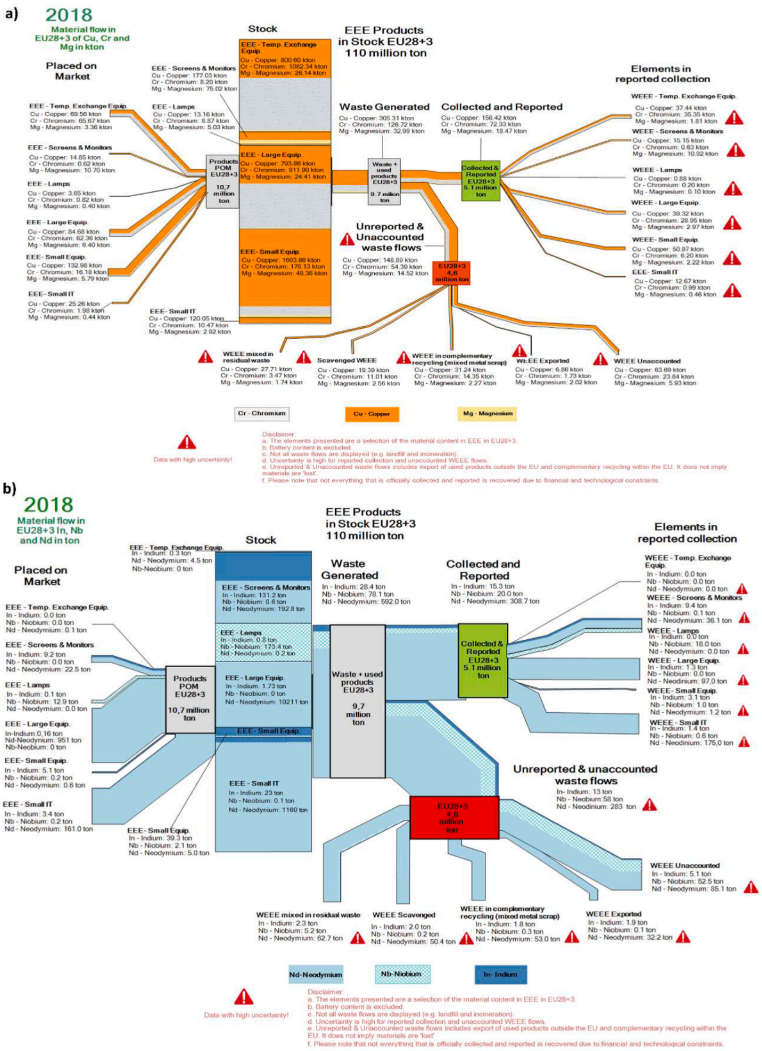
Fig. 3. (a) EEE Stock in Mt for all EU6 collection categories in EU28+3 from 2010 to 2018 (POM and WEEE generated per collection categories can be found in A.17–18.). (b) Stock of Cu contained in IT Equipment per country in EU 28+3 from 2010 to 2018. A.19–23 illustrates the Cu stocks per country for EU 28+3 from 2010 to 2018 for the other EU6 collection categories.

the EU28+3 (Fig. 3 (b)) but also allows the mapping and analysis of material flows (Fig. 4 a,b). An increasing trend in the weight of EEE in stock can be seen from 2010 (101 Mt) to 2018 (109 Mt). In some EU6 collection categories, this trend can be seen more than in others. For example, the weight of large household equipment (col. Cat IV) increased from 37 Mt in 2010 to 43 Mt in 2018, while temperature exchange equipment (col. Cat. I) increased from 20 Mt in 2010 to 24 Mt in 2018. This weight increase is due to technological upgrades and increased sales of PV panels. Small and IT equipment (col. Cat V and VI) showed a consistent increase from 26 Mt in 2010 to 29 Mt in 2018 and from 4.4 Mt in 2010 to 5.7 Mt in 2018, respectively. Screen weights (Col. Cat II) decreased from 12.6 Mt to 7.8 Mt due to a technology shift from cathode ray tubes to flat panel displays for TVs and monitors. Lamp weights also increased slightly from 53 Mt in 2010 to 62 Mt in 2018 due to a change in technology from compact fluorescent lamps to light-emitting diode lamps with longer lifespans. Consumer behaviour, influenced by cultural and economic factors, such as national/regional economic crises, education, and misinformation, directly affects EEE hibernation, which prolongs equipment lifespans and affects WEEE collection and material recovery (Aman et al., 2013; Bertoldi and Atanasiu, 2008; Huisman et al., 2017a).

POM, Stock and WG varies across diffrent EU regions depending on economic development, population, enforcement, consumption patterns etc. These patterns can also be seen in other parts of the world (i.e. Brazil, USA, Australia etc.). In the EU, Northern Europe (NE, 20 kg/inh) has the highest average WG followed by Western Europe (WE,18 kg/inh), Southern Europe (SE, 14 kg/inh) and Eastern Europe (EE, 12.5 kg/inh). In the case of Stock NE has the highest average (138 kg) followed by WE (130 kg), SE (96 kg) and EE (77 kg). Once estimating the different flows per country and knowing the composition of the materials at the product level they can be mapped and analysed at a regional and country level. For example, Fig. 3(b) illustrates that the stock of Cu in (W)EEE IT equipment in EU 28+3 from 2010 to 2018 has steadily increase. As a result, the recovery potential of Cu contained in these products per country can be evaluated. Fig. 3(b) shows that in 2018 Great Britain (23 kt), Germany (21 kt) and France (18 kt) had the highest stock of Cu from IT equipment in their countries, while Greece (0.013 kt), Iceland (0.012 kt) and Malta (0.04 kt) had the lowest stock.

3.2. Quantification of EOL flows of selected elements in 2018

To conduct a more detailed analysis of the contribution of the selected materials in the urban mine a Sankey diagram (Fig. 4 a,b) was created for EU28+3 for the year 2018, following the structure shown in Fig. 1. Of the EEE POM (10.7 million tons), Cu has the greatest contribution (331 kt) illustrating how heavily reliant the EEE industry is on this material and highlighting and supporting why the European Commission deemed it as a strategic raw material. Following closely are Cr and Mg, with 148 kt and 28 kt, respectively. Nd and Nb contribute moderately, accounting for 0.6 kt and 0.08 kt, respectively, while In



Disclaimer:
a. The elements presented are a selection of the material content in EEE in EU28+3.
b. Battery content is excluded.
c. Not all waste flows are displayed (e.g. landfill and incineration).
d. Uncertainty is high for reported collection and unaccounted WEEE flows.
e. Unreported & Unaccounted waste flows includes export of used products outside the EU and complementary recycling within the EU. It does not imply materials are 'lost'.
f. Please note that not everything that is officially collected and reported is recovered due to financial and technological constraints.

Disclaimer:
a. The elements presented are a selection of the material content in EEE in EU28+3.
b. Battery content is excluded.
c. Not all waste flows are displayed (e.g. landfill and incineration).
d. Uncertainty is high for reported collection and unaccounted WEEE flows.
e. Unreported & Unaccounted waste flows includes export of used products outside the EU and complementary recycling within the EU. It does not imply materials are 'lost'
f. Please note that not everything that is officially collected and reported is recovered due to financial and technological constraints.

Fig. 4. a) Material flow in EU28+3 of Cr, Cu and Mg in kilotons b) Material flow in EU28+3 of In, Nb and Nd in tons.

exhibits a smaller contribution of 0.02 kt. These elements play vital roles in manufacturing magnets for electronic devices, wind turbines, and clean energy technologies, making them crucial for technological advancements indicating a level of criticality and highlighting the importance of their sustainable extraction and recycling to ensure a stable supply for future developments. Examining the EEE in stock provides further insights into the material dynamics. With 3509 kt of Cu, 2200 kt of Cr, and 182 kt of Mg, these elements hold significant economic importance, guaranteeing essential resources for future production and manufacturing needs. Additionally, Nd (12 kt), In (0.2 kt), and Nb (0.2 kt) contribute to the stock, underscoring their relevance in maintaining the sustainability of advanced technologies.

The total estimated WEEE generation for 2018 in EU28+3 corresponded to 9.7 Mt of which 5.1 Mt (representing 52 %) was officially reported as collected and recycled, while 4.8 Mt (representing 48 % of the total) corresponded to unreported flows of which 2.6 Mt (representing 27 %) were unaccounted for, indicating a significant gap in the tracking and reporting of these materials. When evaluating the materials it can be seen that there is a significant amount of Cr (54 kt), Cu (149kt), In (0.01 kt), Mg (15kt), Nb (0.06 kt) and Nd (0.3 kt) that are currently unreported and unaccounted for.

When comparing unaccounted and unreported flows, Fig. 4 a,b illustrates that the unaccounted flow is the largest flow of all of them and a significant amount of material is currently undocumented. From the selected elements Cu has the highest volume (64 kt) the highest share corresponds to small equipment (31 kt). This is followed by Cr with 24 kt (highest share found in temperature exchange equipment with 10 kt) and Mg with 6 kt (highest share found in screens with 3kt). In addition, when analysing the unreported flows, WEEE in complementary recycling has the highest volume (47.91 kt) followed by scavenged WEEE (33.02 kt), WEEE mixed in residual waste (32.98 kt) and WEEE exported (10.64 kt), indicating the significance of these materials in informal recycling and scavenging practices. Cu has the highest share of all unreported flows, followed by Cr and Mg. WEEE in complementary recycling can be seen mainly in large equipment (24.52) kt and small equipment (15.01 kt) due to their compositional content and volume making them lucrative targets for scrapping.

In the case of scavenged WEEE, Cu presents the highest share in temperature exchange equipment, followed by large equipment and small equipment mainly driven by the extraction of valuable components such as compressors in fridges, Cu/Fe motors and coils and cables in large equipment. For WEEE mixed in residual waste, the three EU6 collection categories with the highest contribution for EU28+3 are small equipment with 25.53 kt followed by screens with 1.39 kt. The selected materials content in WEEE mixed in residual waste for large equipments was minimal (0.95 kt) and temperature exchange equipment was nonexistent, this can be attributed to the size as well as national and regional monitoring.

To measure the economic impact of these materials, an average material price per flow was calculated as seen in Table 1.

Table 1
Average material price of Cr (Schulte, 2021), Cu (Flanagan, 2022), In (Schuyler Anderson, 2021), Mg (Lee Bray, 2021), Nb (Padilla, 2021), Nd (Garside, 2022) per flow in EU28+3 for 2018. The average conversion rate of 2018 was used for USD to EUR, which was 1 USD = 0.8475 EUR (Exchangerates.org.uk, 2023).

Element / Flow	Average material price (million €/kt)	WEEE Generated (million €)	Collected and recycled (million €)	Unreported flows (million €)	Unaccounted flows (million €)
Cr	9.58	1513.13	689.53	296.88	296.88
Cu	5.47	1653.29	854.02	465.33	470.80
In	266.96	5.34	5.34	0	2.67
Mg	4.05	89.20	72.98	36.49	28.38
Nb	20.12	0.80	0.40	0.20	1.41
Nd	42.21	46.43	12.66	8.44	4.64

WEEE contains a wide range of materials and is a potential source of SRMs. It is important and necessary to quantify all flows especially unreported flows in the EU to have a complete understanding and an overview of SRM in the urban mine. Having this type of estimation can help provide countries and policymakers knowledge on the volume of materials contained in WEEE that is unaccounted for, understand the impact of unreported flows and help improve the formal collection of specific equipment. As a result, they can a) implement and enforce policies that encourage the proper collection, recycling, and disposal of e-waste (e.g. standardization of recycling standards across the EU, establishing accessible and convenient e-waste collection points), b) introduce EPR programs that encourage product design for recycling and creates incentives for manufacturers to use more sustainable materials c) raise public awareness d) encourage recycling and recovery by offering financial incentives or tax breaks to recyclers and businesses that engage in responsible e-waste recycling and resource recovery practices e) encourage circular design (e.g. modular construction and easier disassembly for recycling) f) monitor strategies implemented g) foster international cooperation such as sharing best practices and technology to improve resource recovery.

Unreported and unaccounted flows represent 48 % of the total WEEE generated. While some of these flows might undergo informal recycling elsewhere, there remains a risk of inadequate waste handling, improper disposal, and potential exposure to hazardous substances, posing environmental and health concerns. To put it in perspective, when analysing these flows for the year 2018 a combined loss of € 1.41 billion was estimated for the selected elements (see Table 1). This is a substantial amount which shows the significance of unaccounted flows and the substantial economic impact associated with them. Failing to recover materials found in WEEE means missing out on the opportunity to extract them and utilize them in the manufacturing of new products, leading to a loss of valuable resources. Furthermore, WEEE that is disposed of in landfills, can cause soil and water pollution, leading to increased health risks and remediation costs.

The analysis done highlights the importance of developing robust e-waste statistics not only on a product level but a material level. Furthermore, by measuring this type of flow's future accessibility of these materials, sustainability in all parts of the value chain can be ensured and supply risk can be avoided. Having a broader overview and monitoring will allow policy and decision-makers to develop strategies that are efficient and effective and aim to move more towards a circular economy.

4. Conclusions

The EU's substantial dependence on CRM imports poses a significant economic and security challenge, particularly in an increasingly interconnected and volatile global market. This import reliance is especially pronounced in the electronics industry, which heavily depends on raw materials such as the six analysed materials. The potential outcomes of supply chain disruptions, trade restrictions, and other factors affecting material availability can significantly affect the EU's capacity to satisfy consumer demands, highlighting the need for policymakers to develop resource access safeguarding strategies.

WEEE represents a potential source for recovering CRMs, REE, and base metals. Analysing (W)EEE sales, stocks, and waste flows is instrumental for understanding the significance of these materials in an expanding technology sector and to assess the availability of resources. In 2018, only 52 % of WEEE generated was properly collected and reported, with 48 % being unreported and/or unaccounted for. When analysing the economic impact of these flows a combined loss of € 1.41 billion was estimated for Cr, Cu, In, Mg, Nb and Nd. Improper handling and disposal of WEEE in landfills can pose environmental and health risks, highlighting the need to improve recycling and recovery of materials, increase public awareness and implementing and enforcing appropriate regulations. Overall, these findings underscore the need to increase focus on electronic waste management, particularly in terms of monitoring and reporting unaccounted flows.

Official statistics and forecasts on CRMs in WEEE flows are currently unavailable. Estimating urban mine material content can enhance resource security, reduce supply dependency, improve resource efficiency, and promote circularity. Setting recycling targets and sustainable design practices can incentivize stakeholders and policymakers while improving traceability and understanding of unreported and unaccounted flows can identify areas of concern. Implementing circular strategies can help policymakers make informed decisions and improve SRM recovery.

Furthermore, reducing consumption and/or substituting CRMs should be a priority, however, should be done with caution as potential substitutes could be CRMs and/or be costlier and less effective than the originals. Ecodesign and intelligent product design can contribute to reducing CRM demand hence Research and Development investments are necessary. The EU should actively diversify its CRM sources by exploring new trading partners (non-EU countries), investing in domestic extraction, and supporting sustainable mining practices within the EU.

CRediT authorship contribution statement

Michelle A. Wagner: Conceptualization, Methodology, Software, Visualization, Writing – review & editing, Data curation, Formal analysis, Writing – original draft, Resources, Validation, Investigation. **Hina Habib:** Writing – review & editing, Data curation, Validation, Investigation. **Lucia Herreras:** Data curation, Writing – review & editing. **Ester van der Voet:** Supervision, Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michelle A. Wagner reports financial support was provided by Leiden University Institute of Environmental Sciences.

Data availability

Data will be made available on request.

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Supplementary materials

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