Introduction

The identification and estimation of recoverable critical raw material (CRM) quantities from WEEE management is a complex process and necessarily entails a certain degree of approximation.

The intrinsic heterogeneity of products classified as EEE, differences in treatment technologies, and the hoarding of WEEE (i.e. the phenomenon whereby consumers accumulate old devices, such as smartphones and small household appliances, instead of disposing of them) may result in marked variations in the types and quantities of recoverable CRMs. Furthermore, due to rapid technological evolution, the component composition of EEE varies significantly according to the year of manufacture; this variability is likewise determined by the market segment and price range of the equipment. Finally, it should be acknowledged that the possible presence of CRMs within WEEE does not automatically imply that such materials can in all cases be recovered in an economically and technologically sustainable manner.

Methodology

Accordingly, any assessment of the potential CRM content in WEEE should be based on the six EEE categories used for annual reporting to the European Commission on WEEE management, as defined by Article 31 of Legislative Decree No. 49 of 14 March 2014, implementing Directive 2012/19/EU, and Commission Implementing Decision (EU) 2019/2193:

1. Temperature exchange equipment;
2. Screens, monitors, and equipment containing screens with a surface area greater than 100 cm²;
3. Lamps;
4. Large equipment (with at least one external dimension exceeding 50 cm);
   4a. Large equipment excluding photovoltaic panels;
   4b. Photovoltaic panels;
5. Small-sized equipment (with no external dimension exceeding 50 cm);
6. Small-sized IT and telecommunications equipment (with no external dimension exceeding 50 cm).

For certain EEE categories (categories 1, 2, 3, 4), it is generally easier to develop assumptions regarding the types and quantities of the potential CRMs present, also considering the average "*lifespan*" of these EEE categories. Conversely, for the more heterogeneous and complex categories (categories 5 and 6), assumptions concerning the types and quantities of CRMs present are generally more approximate and subject to greater variability.

Based on the above considerations, a simplified methodological approach for the potential estimation of CRMs in WEEE is outlined below.
The data used for this approach originate from the MUD declarations[1], which are analysed annually by ISPRA for the purposes of the communication to the European Commission under Directive 2012/19/EC on the transmission of WEEE data. These declarations make it possible to determine the quantities recovered for each WEEE category at both national (***Table 1***) and regional level. The regional data used in the present study are provided in a dedicated Excel file (***Annex 1***).

Table 1 Quantity of WEEE managed at national level by category in 2023.

WEEE Category	Total WEEE managed (t/year)
1	130.945
2	85.488
3	9.018
4a	124.904
4b	39.380
5	122.955
6	21.927
National total	**534.616**

Using the MUD declarations as the data source, the list of WEEE treatment and storage facilities that submitted a declaration for the reference year 2023 was obtained. For the purposes of this study, only treatment facilities carrying out actual WEEE recovery operations were considered, whereas storage facilities were excluded. These facilities are listed in a dedicated Excel file (***Annex 2***) and divided into classes according to the quantities managed (0–1,000 t/year; 1,000–10,000 t/year; 10,000–30,000 t/year; >30,000 t/year). For each facility, the specific WEEE categories managed in the reference year are also reported.

For each WEEE category, the CRMs potentially present can be identified based on sector-specific and scientific literature. The literature review further allows the derivation, for each CRM, of

[1] The Environmental Single Declaration Model (Modello Unico di Dichiarazione ambientale – MUD), established by Law No. 70 of 25 January 1994, constitutes the mandatory reporting framework through which economic operators must report, for the year preceding the declaration, the waste generated, collected, transported, and sent for recovery or disposal in the course of their activities.

minimum and maximum content ranges per unit mass of the corresponding WEEE category. This approach enables, at regional scale, a preliminary estimation of the CRMs of interest for each of the six WEEE categories, expressed either as individual chemical elements or as groups thereof (e.g. total metals, precious metals). The methodological approach described can be expressed by Equation (1) below:

$$Q_e = \sum_{i=1}^{6} \quad Q_{WEEE}^{i} \times C_e^{i} \tag{1}$$

where:

- Q_e= estimated quantity of element e (kg/year or g/year)
- Q_{RAEE}^{i}= annual quantity of WEEE managed (t/year), associated with WEEE category i;
- C_e^{i}= content coefficient of element *e*, expressed per unit mass of WEEE (kg/t or g/t), specific to WEEE category *i*.

The potential CRM quantities estimated using this approach are inherently subject to variability, as they are based on declarations submitted by operators for a single reporting year. Similarly, the WEEE categories reported in the database as being managed by individual facilities may also vary due to multiple factors, including the introduction or removal of incentives for the replacement of specific EEE, technological developments, and market dynamics.

In this study, the following groups were considered (***Table 2***): total metals, precious metals, and rare earth elements. Plastics were additionally included, despite not being classified as CRMs, due to their significant quantitative contribution to WEEE.

Table 2. Groups considered

Groups	Elements contained	References
Total metals	iron; copper; aluminium	(European Commission, 2015)
Precious metals	silver; gold; palladium	(European Commission, 2015)
Earth elements	contained in: phosphors; magnets; batteries	(Binnemans et al., 2013; Dhawan and Tanvar, 2022; Yang et al., 2017a)
Plastics	total plastic fraction	(European Commission, 2015)

For each WEEE category, specific content coefficients were applied, derived from European sources and relevant technical literature, in accordance with the EU6 classification adopted for management data.

Total metals

An **indicative estimation** of the total metal content in WEEE was derived with reference to the European Commission report (European Commission, 2015), specifically Section 2.6, "Considerations on consequences and impacts of setting new recovery targets", which provides material content coefficients for the various WEEE categories in accordance with the EU6 classification. The "total metals" group was analysed by considering the following **subgroups**: **iron (Fe), copper (Cu),** and **aluminium (Al)**. The coefficients associated with these metals were applied to the amounts of WEEE managed for each category in order to estimate the potential metal content associated with the treated streams. (***Table 3***).

Table 3. Total metals subgroups

Element	Content coefficients	Unit of measurement	References
Iron (Fe)	Cat 1: 57,7 Cat 2: 25,8 Cat 4a: 53,6 Cat 4b: 53,6 Cat 5: 46 Cat 6: 3,9	wt %	(European Commission, 2015)
Aluminium (Al)	Cat 1: 2,7 Cat 2: 2,8 Cat 3: 12,5 Cat 4a: 7,8 Cat 4b: 7,8 Cat 5: 4,3	wt %	(European Commission, 2015)
Copper (Cu)	Cat 1: 5,2 Cat 2: 3 Cat 4a: 2 Cat 4b: 2 Cat 5: 8,8 Cat 6: 45,4	wt %	(European Commission, 2015)

Precious Metals

Precious metals in WEEE are primarily concentrated in printed circuit boards (PCBs), i.e. electronic boards (Cayumil et al., 2016; Lu and Xu, 2016), although they may also be present in other electrical and electronic components such as contacts, connectors, and solder joints (Szałatkiewicz, 2014) . This evidence is further supported by the findings of the FutuRaM project, which indicate that several critical and precious metals are predominantly concentrated in specific electronic components, leading to a strong dependence of overall contents on the composition of the WEEE stream analysed (Iattoni, 2025). Differences in the proportion of electronic components across equipment types lead to variability in precious metal content among WEEE categories. Specifically, categories 2 (screens), 4b (photovoltaic equipment), 5 (small equipment), and 6 (small IT and telecommunications equipment), which are characterised by a higher degree of electronic integration, are more relevant with respect to the presence of silver (Ag), gold (Au), and palladium (Pd). These metals have particular relevance both for the economic value associated with WEEE and for the development of targeted recovery strategies aimed at maximising the efficiency of recycling processes, particularly during the pre-treatment and refining stage. These metals have particular relevance both for the economic value associated with WEEE and for the development of targeted recovery strategies aimed at maximising the efficiency of recycling processes, particularly during the pre-treatment and refining stages. The literature indicates that Ag, Au, and Pd represent the main precious metals of interest in WEEE, due to their concentration in electronic components and their high market value (Chancerel et al., 2009). Accordingly, the estimation of precious metals, as presented in ***Table 4***, was performed by applying category-specific content coefficients derived from the European Commission report on material composition (European Commission, 2015).

Table 4. Content coefficients adopted for the precious metals group

Element	Content coefficients	Unit of measurement	References
Silver (Ag)	Cat 2: 0,005024 Cat 4a: 0,005986 Cat 4b: 0,005986 Cat 5: 0,001629 Cat 6: 0,009017	wt %	(European Commission, 2015)
Gold (Au)	Cat 2: 0,00215 Cat 4a: 0,000003	wt %	(European Commission, 2015)

Element	Content coefficients	Unit of measurement	References
	Cat 4b: 0,000003 Cat 5: 0,000368 Cat 6: 0,002539		
Palladium (Pd)	Cat 2: 0,000968 Cat 5: 0,000102 Cat 6: 0,000678	wt %	(European Commission, 2015)

Rare earth elements

Rare earth elements (REEs) constitute a minor but relevant component of WEEE, being associated with materials and components of high technological value (Balaram, 2019). Their occurrence in WEEE streams is not homogeneous and is largely concentrated in specific component types. Specifically, REEs are primarily associated with neodymium–iron–boron (NdFeB) permanent magnets, used in hard disk drives, electric motors, fans, and loudspeakers, as well as with the phosphors of fluorescent lamps (Schaeffer et al., 2018). Experimental studies have shown, for example, that a fraction of these elements may be present in the **fine/residual fractions** generated during mechanical pre-treatment processes (Ueberschaar et al., 2017). Evidence of this heterogeneity is provided by Puype et al., who document the presence of several rare earth elements (e.g. Ce, Dy, La, Nd, Pr, and Y) in polymeric materials contaminated by WEEE streams, suggesting that these elements may also be present in non-metallic matrices at low concentrations (Puype et al., 2015). The literature also provides data for selected components, such as **printed circuit boards (PCBs)**, which may exhibit locally elevated concentrations of specific elements, with reported values for **Nd** reaching up to several hundred ppm (Stratiotou Efstratiadis and Michailidis, 2022). The relevance of these elements in the context of urban mining is confirmed, at the European level, by the ProSUM project, which includes rare earth elements among the materials of interest associated with EEE/WEEE streams (Huisman et al., 2017). REEs were considered, for estimation purposes, by distinguishing the main types of components responsible for their presence in the treated streams (***Table 5***). Specifically, REEs were grouped into three main categories: those contained in the phosphors of fluorescent lamps, those associated with neodymium–iron–boron (NdFeB) permanent magnets, and those present in nickel–metal hydride (NiMH) rechargeable batteries.

Table 5. Main WEEE components containing rare earth elements

Component	Rare earth elements present	Main applications	References
Phosphors	Yttrium (Y), Europium (Eu), Terbium (Tb), with minor contributions of Cerium (Ce) and Lanthanum (La)	fluorescent lamps, display devices	(Dhawan and Tanvar, 2022)
Permanent magnets	Neodymium (Nd), with possible contributions of Praseodymium (Pr), Dysprosium (Dy), and Terbium (Tb)	Electric motors, hard disk drives, fans, loudspeakers	(Yang et al., 2017a)
NiMH batteries	lanthanum (La), Cerium (Ce), Neodymium (Nd), Praseodymium (Pr)	Rechargeable batteries for electronic devices	(Binnemans et al., 2013)

The REE content associated with phosphors was estimated with reference to Cat 3 (lamps). The literature indicates that phosphors account for up to approximately 2% by weight of the total lamp mass, whereas phosphors recovered from fluorescent lamps exhibit REE contents in the range of about 9–26% by weight. the REEs present in phosphors consist predominantly of yttrium (Y), europium (Eu), and terbium (Tb), with minor contributions from cerium (Ce) and lanthanum (La). For estimation purposes, a central scenario was adopted, assuming a phosphor fraction equal to 2% of the lamp mass and an average rare earth content in phosphors of 15%, corresponding to an intermediate value within the range reported in the literature (Table 6). The quantity of REEs associated with phosphors was calculated according to the following relationship:

$$REE_{Phosphors}\,[t] = M_{WEEE,Cat.3}\,[t] \times 0{,}02 \times 0{,}15 \qquad (2)$$

This approach is consistent with the literature and allows for a conservative estimation of the contribution of rare earth elements associated with fluorescent lamp phosphors (Dhawan and Tanvar, 2022). The occurrence of neodymium–iron–boron (NdFeB) permanent magnets in WEEE is primarily associated with equipment incorporating electric motors, hard disk drives, fans, and other electromechanical systems. Literature data on typical NdFeB magnet masses in end-of-life products indicate values of approximately 10–20 g for hard disk drives, 40–60 g for refrigerators, and 80–180 g for washing machines, supporting a greater prevalence of magnets in Categories 6 and 5 (Smith et al., 2022). The REE content in NdFeB magnets is approximately 31–32% by weight (Yang et al., 2017a). In the absence of official coefficients for the direct estimation of magnet masses from WEEE streams, explicitly stated methodological assumptions were adopted, derived from typical magnet masses per unit product and from the composition of the streams. Specifically, a coefficient $f_{mag,c}$, expressed as kilograms of NdFeB magnets per tonne of WEEE of category c, was defined, assuming a central scenario of 5 kg/t for Category 6 and 1 kg/t for Category 5. The mass of NdFeB magnets associated with each WEEE category was estimated using the following relationship:

$$M_{NdFeB,c}\,[t] = M_{RAEE,c}\,[t] \times \frac{f_{mag,c}}{1000} \tag{3}$$

Accordingly, the amount of rare earth elements contained in the magnets was calculated by applying the characteristic REE weight fraction of NdFeB magnets to the estimated magnet masses (***Table 6***).

The REE content associated with nickel–metal hydride (NiMH) rechargeable batteries was estimated by considering exclusively Cat 6, which includes small equipment characterised by widespread use of rechargeable energy storage systems. The composition of NiMH batteries was derived from the scientific literature, which indicates a mischmetal content of approximately 8–10% by weight, primarily composed of lanthanum (La), cerium (Ce), praseodymium (Pr), and neodymium (Nd) (Binnemans et al., 2013). In the absence of national statistical data on the mass of NiMH batteries in WEEE streams, a conservative methodological assumption of 2 kg of NiMH batteries per tonne of WEEE in Cat 6 was adopted. The quantity of REEs associated with NiMH batteries was therefore derived by applying a 10% weight fraction to the corresponding NiMH battery masses (***Table 6***). The calculation was performed using the following relationship:

$$REE_{NiMH}\,[t] = WEEE_{Cat.6}\,[t] \times \frac{m_{NiMH}}{1000} \times f_{REE} \tag{4}$$

where:

- REE_{NiMH} is the mass of REEs (La, Ce, Pr, Nd) associated with NiMH batteries [t];
- $WEEE_{Cat.6}$ is the mass of WEEE in Category 6 managed in the reference year [t];
- m_{NiMH} is the mass of NiMH batteries per tonne of WEEE, assumed to be equal to 2 kg/t;
- f_{REE} is the weight fraction of rare earth elements in NiMH batteries, assumed to be equal to 0,1.

Table 6. Content coefficients used for rare earth elements estimation

Component	Content coefficients	Unit of measurement |	References
Phosphors	Cat 3: 0,003	t REE / t WEEE	(Dhawan and Tanvar, 2022)
NdFeB magnets	Cat 5: 0,00031 Cat 6: 0,00155	t REE / t WEEE	(Binnemans et al., 2013)
NiMH batteries	Cat 6: 0,00020	t REE / t WEEE	(Yang et al., 2017b)

Plastics

Plastics were included in the analysis despite not being classified as CRMs, as they represent a quantitatively significant fraction of WEEE. Their presence significantly influences the overall composition of treated streams and the strategies adopted for material management and recovery. The literature highlights that the proportion of plastics in WEEE varies according to equipment type and stream composition (Cardamone et al., 2021). Boudewijn et al. document a marked heterogeneity of the plastic fraction across WEEE types, reflecting significant category-specific variability (Boudewijn et al., 2022). The plastic fraction was estimated by applying category-specific content coefficients for each WEEE category, as defined in European Commission reports on material composition (European Commission, 2015). The coefficients were applied to the quantities of WEEE managed in order to estimate the potential quantities of plastics associated with the treated streams (***Table** 7*).

Table 7. Coefficients adopted for the plastics group

Element	Content coefficients	Unit of measurement |	References
Plastics	Cat 1: 24,7 Cat 2: 24,5 Cat 3: 10,9 Cat 4a: 10,4 Cat 4b: 10,4 Cat 5: 26,3 Cat 6: 35,8	wt %	(European Commission, 2015)

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