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RESEARCH ARTICLE

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Thermodynamic rarity of electrical and electronic waste

Assessment and policy implications for critical materials

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Abstract

The strategic relevance of extracting raw materials from waste from electrical and electronic equipment (WEEE) in the EU is increasing due to value chain risks caused by geopolitical instability, accessibility of specific minerals, and decreasing reserves due to growing extraction rates. This article examines the quantities of so-called critical raw materials (CRMs) originating within WEEE streams from a depletion perspective. Presently, current recycling targets are based solely on mass collection and recycling rates. We examine the potential limitations of this approach using an exergy-based indicator named thermodynamic rarity. This indicator represents the exergy costs needed for producing materials from the bare rock to market. The case of Italy is used to explore the application of the indicator at the macro (national) and micro (company) level for the product categories “small electronics” and “screens and monitors.” Our estimations show significant differences between the mass and rarity of materials within Italian WEEE streams. While iron accounts for more than 70% of the weight of the product categories analyzed, it accounts for less than 15% of the rarity. Similarly, several CRMs with a small mass have a higher rarity value, for example, tungsten with less than 0.1% of the mass and over 6% of the rarity. The policy context is reflected upon, where it is argued that thermodynamic rarity can provide novel insights to support end-of-life WEEE decision-making processes, for example, target development and recycling standards setting to help prioritize material monitoring and recovery options.

KEYWORDS

circular economy, critical raw materials, eco-design, exergy, extended producer responsibility, policy analysis, waste from electrical and electronic equipment

1 | INTRODUCTION

1.1 | Background

The strategic relevance of extracting raw materials from waste from electrical and electronic equipment (WEEE) in the EU is increasing due to value chain risks caused by geopolitical instability, accessibility of specific minerals, and decreasing reserves due to growing extraction rates (Bobba et al., 2020). Present consumption patterns raise the issue of future demand bottlenecks for certain materials, depletion, and future unavailability unless actions to reduce, conserve, and increase recycling efforts are taken (Henckens, 2021; Valero et al., 2018).

Among those elements, the so-called "critical raw materials" (CRMs) are of particular interest to the EU as they represent materials with a high supply risk and a high economic value, for example, indium and cobalt[1] (European Commission, 2020). In addition to CRMs, geologically scarce materials are those that are characterized by a relatively low concentration in the crust and are thus at the risk of early exhaustion, due to physical availability and demand, for example, copper and antimony (Henckens et al., 2016b; Ortego et al., 2018b). Despite the EU outlining the importance of CRMs in recent years (European Commission, 2020), they are not explicitly integrated within general EEE or WEEE legislation yet (Arduin et al., 2020). In this context, (W)EEE is currently governed under two key bodies of legislation specifically related to product design and WEEE. In particular, "product design" is regulated through the Eco-Design Directive 2009125/EC (European Parliament (EP) & European Union, 2009) and Energy Labeling Regulations 2017/1369 (EPt & The Council Of The European Union, 2017), which set guidance primarily on energy labeling and in-use efficiency measures. Whereas, WEEE is governed under Directive 2002/96/EC (EP & Council, 2002) and its recast 2012/19/EU (EP & Council, 2012), which employs the principle of extended producer responsibility (EPR) by giving market actors either organizational or financial responsibility for the collection and recycling. Other noticeable pieces of legislation include the Waste Framework Directives (European Commission, 2008; WFD, 2018/851, 2018), which sets further requirements on EPR, and chemicals legislations, for example, the REACH (European Parliament, 2006), which details, monitors, and restricts the use of certain substances. Besides, the CENELEC EN 50625 Standards assist WEEE actors in fulfilling the previously mentioned Directive's requirements. Due to the focus on mass, both in the collection and recycling of WEEE, there is a broader issue of whether the end-of-life (EoL) stage appropriately considers and integrates elemental scarcity, both in monitoring and prioritization in recovery operations (Arduin et al., 2020).

The ambitions of European circular economy (CE) policies center around stimulating more efficient use of natural resources and preventing resource depletion through various strategies, including EPR (European Commission, 2020). The quantities and total demand of specific elements (against their use within other products) vary depending on the product in question, for example, 88% of indium was used in EEE, antimony was 41%, and terbium was 88% (European Commission, 2018). CRMs material flows have been mapped within the EU (Bobba et al., 2020; Saurat & Bringezu, 2008). WEEE was identified as a significant source of CRMs, while higher recycling efforts in combination with substitution (where possible), product life time extension and reduced demand have been proposed to mitigate long-term bottlenecks (European Commission, 2018; Valero et al., 2018). Conservation (either through product lifetime extension or recycling) can, but not always (Zink & Geyer, 2017), mitigate the broad array of socio-environmental damages associated with mining (Marcantonio et al., 2021; Tsurukawa et al., 2011). Yet, the recycling of geologically scarce and CRMs differs per material due to a combination of low collection rates, varying efficiencies of suitable technologies, product design issues, for example, dissipative losses (Ciacci et al., 2015), low concentrations in products, and a lack of secondary markets (Bobba et al., 2020).

1.2 | Research gap and aim of this study

Van Nielen et al. (2022) studied the recyclability of CRMs noting that industrial-scale recycling for most "minor metals" (rare earth elements, precious metals, and speciality metals) is currently non-existent. Furthermore, considerable process losses might occur during the treatment of WEEE, which are not considered in the general legislation and method to calculate recycling rates in Directive 2012/19/EU (Arduin et al., 2020). In a study on WEEE recycling outcomes, Arduin et al. (2020) showed that the recycling rates of materials varied significantly, with base and precious metals recovered more than CRMs. The authors stressed specific indicators for documenting such scarce materials are needed. However, beyond documenting what elements are present in electronic waste streams, a more fundamental question of *which* elements should be prioritized (from a broader conservation perspective) for recovery and *how* this relates to WEEE policies is still lacking in the literature.

Although CRMs considerations are included in the consultations of specific products, for example, computer servers (European Commission, 2013), the vital requirements that effects EEE are stipulated in the WEEE Directives. These include mandated collection and recycling targets for different WEEE categories. As of 2019, the current targets specify the collection of 65% of electronic products put on the market (calculated from the total weight collected and the average weight of electrical products put on the market for the previous 3 years). The Directive further specifies preparing for reuse recycling targets for specific product types, for example, 70% (by weight) for screens and monitors and 55% for small equipment and information technology (IT) and telecommunications.

An alternative to mass-based targets and how to assess the priority of elements was analyzed by Ortego et al. (2018a, 2018b) using an exergy-based indicator termed *thermodynamic rarity* (TR), applied to the recycling of automotive vehicles in Europe. TR is calculated by assuming elements' exergy value to account for their relative abundance in the Earth's crust. The logic is that as demand for energy and materials increases and mineral reserves decrease, the need to conserve those materials that are more intensive and difficult to mine will grow (Valero & Valero, 2015). The research used aggregated and estimated data. Still, it allowed the authors to illustrate: (i) the discrepancy between the mass and rarity of material and (ii) the limitations of collection and recycling targets based on mass. The indicator illustrates *which* materials (from a conservation/depletion) perspective are rarer and, thus, valuable. Although the indicator has been applied broadly to the energy transition (Valero et al., 2021) and the composition of mobile phones (Torrubia et al., 2022), no study has applied it to the WEEE product category level, for example, screens.

In this context, the objective of this study is to apply the TR indicator to WEEE sector to explore the issues linked to WEEE population and recycling policies. To provide a more consistent evaluation, we opt for a dual approach to examine WEEE generation at the macro and aggregate (national) level and further complement this at the micro (company) level. In the first case, we use estimated national data, while in the latter case, we identify a sample among WEEE processed by a processing facility. Both levels of analysis focus on the case of Italy. This research aims to (a) estimate the quantities of CRMs (national and company level) and apply a TR assessment to compare the materials' mass and rarity. Based on the insights, we (b) reflect on the theoretical implications for current policy practices for WEEE, including recovery targets. In essence, can TR be a useful tool to help monitor and prioritize which materials should be recovered by showing the hidden value of different materials? This study connects the technical on-the-ground flows of materials within a broader sustainability policy frame.

This study is structured as follows: after this introduction section, we expand on the selected theoretical approach of TR and the research design, including the case study and sampling approach (see Section 2). Then, the results section provides both the quantitative results of the analysis (mass and rarity comparison) as well as a critical policy reflection (Section 3) before we conclude (Section 4).

2 | MATERIALS AND METHODS

2.1 | Theoretical approach

This research follows the methodological approach first demonstrated by Ortego et al. (2018a, 2018b) and validated by Torrubia et al. (2022) to examine the rarity of different materials within the WEEE streams using an exergy-based indicator termed TR as proposed by Valero and Valero (2015).

As Valero and Valero (2012, 2013, 2015) outlined, *TR* provides a methodology to signify the exergy requirements needed to extract and process elements from the Earth's crust into a useful commodity or element. In this context, exergy is defined as the maximum amount of work that may be theoretically performed by bringing a resource into equilibrium with its surrounding environment through a reversible process (Perrot, 1998). All substances and elements have definable exergy against a defined external environment. In their research, Valero and Valero (2015) presented a "dead state" of a hypothetical planet with exhausted resources termed Thanatia. Based on this reference point, they calculated the exergy costs needed to mine an element from this dead state to the current state of mineral deposits (named *exergy replacement costs)* and energy needed to extract and refine a mineral from current mineral deposits using current technologies to produce a useful commodity (named *embodied exergy costs)*. Estimates for the mineral quantities were based on Cox and Singer (1987). The sum of *exergy replacement costs* and *embedded exergy costs* is the TR. As argued by Ortego et al. (2018a, 2018b), a mineral is regarded as valuable for two reasons: (1) they are scarce (physical availability) and/or (2) they are expensive to obtain with regard to extraction costs. This latter point relates to the energy requirements to obtain and refine a specific mineral to make a useful element through beneficiation and refinement. Such costs increase when ore grades decline.

TR allocates a value (exergy) to minerals and elements based on their relative abundance in the Earth's crust and the energy intensity needed to refine them. The geological occurrence of high concentrations of elements within mines (i.e. the elements not being lightly dispersed) saves large quantities of energy during extraction (Ortego et al., 2018b; Valero & Valero, 2012). Geologically scarce or rare elements generally have a higher TR value due to their dispersed quantities and, therefore, higher extraction, beneficiation, and refining costs.

In contrast to other indicators that focus on material assessments, such as material footprints (Sen et al., 2019; Wiedmann et al., 2015), raw material equivalents (Eurostat, 2001), or ecological footprints (Rees, 1992), TR reflects the physical criticality of mineral resources through a consistent exergy measurement, indicating which materials (from a long-term conservation perspective) are most valuable. Given the emphasis on physical rarity at the elemental level, we adopt it for this study.

TR should not be conflated with recyclability. The former allocates a value (exergy) to the elemental composition of a product based on its physical abundance in nature and the exergy needed to extract and refine them. The comparison between recycling requirements and TR has been theoretically explored by Valero and Valero (2020) and Valero et al. (2021), where they outlined the necessity effectively monitoring the quality of waste streams to support the closing of loops. However, this research does not consider the exergy requirements needed to extract specific elements from WEEE as a means of comparison was not available. Such work is currently explored in the product category mobile phone printed circuit boards (Torrubia et al., 2022). Instead, we examine the application of the indicator but in the novel context of WEEE EU policies. While the technical

TABLE 1 Italian WEEE categories and how they align with those in the WEEE Directive

Category name	Description	EU categories(Annex 4 WEEE Directive 2012)
R1	Cooling and freezing equipment	1 Temperature exchange equipment
R2	Large household appliances	4 Large equipment
R3	TVs and monitors	2 Screen, monitors.
R4	Mixed WEEE	5 & 6 Small equipment and small IT and telecommunications
R5	Lamps	3 Lamps

constraints of CRMs recycling are not assessed in this study (see CEWASTE, 2021 and Section 3.3 for limitations), the indicator provides a theoretical insight into the rarity of the elements currently available at the point of waste generation and treatment. It thus enables a more dynamic view on the issues within EU policy.

2.2 | Research design

2.2.1 | Selected case study

WEEE recycling in the EU generally is carried out according to the following consecutive processes: after collection/sorting and transportation to a treatment plant, WEEE goes through manual and/or mechanical separation and/or dismantling (CEWASTE, 2021). The following process includes the shredding of equipment into small pieces, electromagnetic separation or optical sorting, and finally the separation of ferrous and non-ferrous metals as well as plastic and glass fractions. PCBs can undergo additional processes to recover the rare materials they contain (Dutta et al., 2018). For a clear overview of the specific steps, standards and procedures for EoL of WEEE see CENELEC (2016).

This research used a case study of Italy to explore the application of the rarity indicator in the context of CRMs within WEEE. A case study is an in-depth examination of a specific case in question (Yin, 2003); while not allowing for generalizable results, it enables novel theoretical insights to be raised and explored, this being the impact of WEEE policies. The case of Italy is examined on two levels: macro (national) and micro (company), to compare the mass and rarity of materials within WEEE streams. The national level used aggregated data on WEEE generation (Section 2.2.2), while the company level examined specific WEEE entering a processing facility. Detailed data of which elements were recovered in Italy were unavailable, meaning our macro analysis focused only on the composition of WEEE generated. This complementary approach allows a more dynamic understanding of the differences between policy and national and on-the-ground effects.

This study used a sampling approach that identified the products present in the waste streams at the company level. The sample was selected randomly among the WEEE boxes that were sent to the treatment facility site in Italy. Applying these procedures was necessary because of the rapid innovation and varying lifespan of electronics (Bakker et al., 2014), the characterization of the WEEE population is a complex task (Rigamonti et al., 2017). Indeed, all WEEE categories include a large number of devices characterized by a complex mixture of materials and components that changes over time and space in percentage and size in each WEEE category (e.g., fridge, lamps, monitors) as well as in similar equipment (Mählitz et al., 2020). In addition, although the collaboration with the WEEE processor allowed the understanding of the main EoL treatment processes of EEE, only limited aggregate and detailed company inventory data were available. Therefore, the sampling approach centered around creating an accurate insight or snapshot into product flows and waste at a particular time.

Materials recovered from the company level treatment facility via recycling include aluminum, copper, steel, iron, plastic, and glass. The company's recycling rate was estimated to be 96%.[2] PCBs are manually separated and sold for subsequent processing by a different company, from which no data was shared due to reservations over its sensitive nature. Thus, we assume, based on literature and research on PCB and rare materials processors in Europe, that elements recovered include: copper, nickel, gold, silver, tin, platinum, and palladium (Dutta et al., 2018; Sheng & Etsell, 2007). For an overview of the processes for rare element recovery from PCBs see Wang and Gaustad (2012).

2.2.2 | Data gathering and analysis

Italy organizes and reports its WEEE under five categories, which differs to EU categories (Table 1). See Magalini et al. (2012) for an overview of WEEE in Italy. This study looked at R3 TVs and monitors and R4 mixed electronics product categories. These two categories were chosen due to CRMs presence and heterogeneous nature as they contain various components, for example, base metals, PCBs (Rigamonti et al., 2017). Categories R1 and R2 were not chosen due to their inaccessibility at the processing plant. R5 was not treated at the site and was, therefore not chosen. This choice of product categories informed the selection of data at the national level.

TABLE 2 Overview of elements assessed in this study and summary of key information

Element name	Included in the 2020 EU critical raw material list (European Commission, 2020)	Ultimately available resources (estimated and rounded Mt) (Henckens, 2021)	Indicative exhaustion period (years after 2015) (Henckens, 2021)	End-of-Life recycling rate (estimated) (United Nations Environment Programme, & International Resource Panel, 2011)
Aluminum (Al)	No	10,000,000	10,500	>50%
Antimony (Sb)	Yes	100	150	1-10%
Bismuth (Bi)	Yes	20	150	<1%
Chromium (Cr)	No	35,000	350	>50%
Cobalt (Co)	Yes	3000	1100	>50%
Copper (Cu)	No	10,000	100	>50%
Dysprosium (Dy)[b]	Yes	20,000	1200[d]	>1%
Gold (Au)	No	2	150	>50%
Indium (In)	Yes	30	250	<1%
Iron (Fe)	No	6,000,000	1100	>50%
Lithium (Li)	Yes	2000	1600	<1%
Magnesium (Mg)	Yes	3,000,000	40,000	25-50%
Molybdenum (Mo)	No	200	200	25-50%
Neodymium (Nd)[b]	Yes	20,000	1200[d]	>1%
Nickel (Ni)	No	8000	450	>50%
Palladium (Pd)[a]	Yes	3	5300[c]	>50%
Platinum (Pt)[a]	Yes	3	5300[c]	>50%
Silver (Ag)	No	20	150	>50%
Terbium (Tb)[b]	Yes	20,000	1200[d]	>1%
Tin (Sn)	No	300	700	>50%
Tungsten (W)	Yes	200	600	10-25%
Zinc (Zn)	No	30,000	400	>50%

[a]Platinum group metals are: ruthenium, rhodium, palladium, osmium, iridium, and platinum.
[b]REE are scandium, yttrium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and promethium.
[c]Rare earth metal exhaustion rate are given collectively based on (Henckens, 2021).
[d]Platinum group metal exhaustion rate is given collectively for all metals. The chosen elements were selected from Henckens (2021) and Arduin et al. (2020).

Company level data were gathered through a point-in-time sampling approach for R3 and R4. The R4 category contained a mixture of IT, consumer electronics, tools, and toys, whilst the R3 category contained computer and TV screens and monitors (for a complete overview of all the specific products, see the Supporting Information). Three samples were carried out at the company between December 2020 and May 2021, where the WEEE were sampled and categorized according to products, brands, and models. Sampling times were partly limited and constrained by the Covid-19 restrictions in Italy during this period. In total, an inventory of 680 products (90 R3 and 590 R4) with a total weight of 4285.8 kg was collected (detailed data are in the Supporting Information).

After organizing the sample data and cross-checking it with available online documents and technical reports on brands and models to ascertain if any information was available on the material composition, the next step was to select the elements to be assessed. For this, we selected a number of elements based on the following two factors: (1) elements that the processing company extracted in the case study, for example, aluminum, copper, and iron, and (2) elements that are often present in electronics that are considered either “rare and critical” or (geologically) scarce (Arduin et al., 2020; Henckens, 2021). A complete overview of the selected elements and noticeable features are presented in Table 2.

For exploring the material composition of WEEE at the national and company level, the ProSUM dataset held by the United Nations University (UNU) (Huisman et al., 2017) was used. The UNU dataset includes an estimation of elemental composition and weight for the average product (within each EU member state) for 1980–2020. Certain elements in the dataset are characterized by low confidence[3] due to the scattered and incomplete nature of data (see Huisman et al., 2017). However, this dataset contains the most comprehensive overview of WEEE products’ composition available at the time of writing, and was thus chosen to be used. Data on the national level included the estimated elemental composition for the WEEE generated in Italy (Huisman et al., 2017). We set the reference year at 2020,[4] which was when this study commenced and selected the product categories based on the availability of data at the company level (see later). The data used to inform the subsequent analysis are based on a combination of measurement and reported data, which incorporates the varying assumptions of the dataset. The results in Section 3 are presented as estimation as opposed to concrete results.

All the elements presented in Table 2 were used in the TR assessment. Due to the vast array of products and brands within the company sample, for some of which the technical reports were unrecognizable, it was assumed that year of production for products in the sample (according to Magalini et al., 2014 and Forti et al., 2018), and therefore reference point in the ProSUM dataset, corresponded to the assumed average life of said product for Italy. The aggregated weights for each element for all R3 and R4 products are provided in the Supporting Information.

The TR assessment for each of the elements for the aggregated weights of each product category was calculated using Equation (1). The calculation procedures are provided in the Supporting Information.

$$R_A = \sum_{i=1}^{n} m_i \cdot R_i \tag{1}$$

where R_A is TR (kJ/g) of the product category A (R3 and R4). m and R represent, respectively, the mass (g) and TR—as calculated by Ortego et al. (2018b) and summarized in the Supporting Information—of the ith element assessed.

After applying Equation (1), we calculated the relative percentage of the TR of each element in the sample (per product category) against the total TR for the same product category. The analysis compares the differences of the relative percentages between a mass-based approach (as used in the WEEE Directive) and a TR approach for the materials in each product category. This was done at the national and company level. To provide clear communication, the estimations are presented into two clusters based on the element's mass share: one includes the materials below 0.1 wt% of the total weight, and the second the others. Presenting the mass and rarity values on these two levels provides an opportunity to theoretically reflect on the applicability of the indicator and effect of recycling practices in the context of the EU policy regime.

3 | RESULTS AND DISCUSSION

3.1 | Mass and rarity comparison (national and company level)

The comparison between mass and rarity for both levels is provided in Tables 3 and 4. We present the estimations first on the national level. Next, we complement this aggregate analysis with more precise data at the company level. The values presented in the subsequent sections should be considered estimations for the specific case study in question, not generalizable.

3.1.1 | National level

The mass and rarity estimates for the two product categories for WEEE generated in Italy are presented in Table 3 and visualized in Figure 1. The vast majority of the mass is accounted for by three metals: aluminum, copper, and iron. The major metals (those above 0.1% of the total mass share) account for 99.94% (R3) and 99.83% (R4) of the total mass share of the product category. However, applying the TR indicator reveals 14 materials with mass share below 0.1% that account for 21.07% (R3) and 4.57% (R4) of the total TR. The TR weighting for the R3 categories stands out as exceptionally high against the product category mass share of 0.06%. We examine several key differences in each product category below.

For R3, the most noticeable change is the lower value for iron. Conversely, antimony is higher with 4.1% mass to 9.3% rarity and aluminum with a 14.3% mass to over 44% of the total rarity. Several of those materials that accounted for less than 0.1% of the total had significantly higher TR values. These include gold, which rose from 0.004% of the mass to 10.784% of the rarity; indium, with 0.005% of the mass to over 8% of the rarity; and tungsten with 0.004% of the mass to 0.149% of the rarity. Both indium and tungsten are CRMs, which indicates their increased significance through a TR perspective. For R4, higher TR values include aluminum, 14.58% of the mass and 54% of the rarity; nickel, 0.73% of the mass and 3.1% of the rarity; and tungsten 0.14% of the mass and 6.25% of the rarity. Of the minor metals, silver was higher with 0.004% mass to 0.18% rarity and gold from 0.001% mass to 2.46% rarity. Similarly to R3, iron saw a lower value from 73.23% mass to 13.13% rarity. The estimations from the national level indicate a discrepancy between mass and rarity, particularly for several key materials, for example, tungsten and indium.

3.1.2 | Company level

Based on information obtained from the processing plant, iron, copper, and aluminum are recovered. As described earlier, we could not ascertain a definitive list of the specific materials recovered from the PCBs as a different company did these. According to previous studies (Dutta et al.,

TABLE 3 Estimated differences between mass and rarity at the national level

National level							
R3				**R4**			
Elements	Mass	+/−	Rarity	Elements	Mass	+/−	Rarity
Fe (A)	70.2651%	−	10.3880%	Fe (A)	73.3262%	−	13.1472%
Al (A)	14.3861%	+	44.1394%	Al (A)	14.6037%	+	54.3409%
Cu (A)	6.7956%	+	10.9897%	Cu (A)	8.3260%	+	16.3297%
Sb (A)	4.1376%	+	9.3703%	Cr (A)	1.3282%	−	0.3058%
Mg (A)	2.7297%	−	1.8465%	Zn (A)	0.9263%	+	1.0269%
Zn (A)	0.8043%	−	0.7352%	Ni (A)	0.7284%	+	3.1082%
Cr (A)	0.3124%	−	0.0593%	Mg (A)	0.3425%	−	0.2810%
Sn (A)	0.2808%	+	0.5905%	Sn (A)	0.2446%	+	0.6238%
Ni (A)	0.2313%	+	0.8138%	W (A)	0.1385%	+	6.2567%
Ag (B)	0.0152%	+	0.6310%	Co (B)	0.0144%	+	0.8908%
Co (B)	0.0139%	+	0.7103%	Nd (B)	0.0086%	+	0.0325%
Nd (B)	0.0108%	+	0.0335%	Sb (B)	0.0068%	+	0.0187%
In (B)	0.0052%	+	8.7423%	Ag (B)	0.0035%	+	0.1785%
W (B)	0.0040%	+	0.1493%	Dy (B)	0.0008%	+	0.0033%
Au (B)	0.0035%	+	10.7844%	Au (B)	0.0007%	+	2.4652%
Bi (B)	0.0022%	+	0.0055%	In (B)	0.0004%	+	0.8997%
Mo (B)	0.0008%	+	0.0041%	Pd (B)	0.0002%	−	0.0000%
Pd (B)	0.0007%	−	0.0001%	Mo (B)	0.0001%	+	0.0005%
Dy (B)	0.0006%	+	0.0020%	Tb (B)	0.0001%	+	0.0003%
Pt (B)	0.0000%	+	0.0048%	Li (B)	0.0000%	+	0.0002%
Li (B)	0.0000%	−	0.0000%	Bi (B)	0.0000%	+	0.0001%
Tb (B)	0.0000%	−	0.0000%	Pt (B)	0.0000%	+	0.0901%

A, those elements above 0.1% of the total mass; B, those below.

2018; Sheng & Etsell, 2007), we assume that the materials that are potentially recovered if the processes from these studies are applied are: copper, gold, silver, tin, palladium, and platinum. The specific recovery rates of those materials and subsequent final quantities are unknown. Based on this, we can infer that the materials that are lost in this process include: antimony, bismuth, chromium, cobalt, dysprosium, indium, lithium, magnesium, molybdenum, neodymium, terbium, tungsten, and zinc. This equated to a loss of TR of 38% (R3) and 10% (R4). With the exception of chromium, zinc, and molybdenum all these materials lost are EU CRMs. The losses of these materials raise an issue not only from preventing further resource depletion but also that many of these materials are essential for modern economies and emerging green technologies, that is, cobalt and tungsten (Bobba et al., 2020; Tkaczyk et al., 2018).

The mass and rarity estimations of R3 and R4 categories are reported in Table 4 and visualized in Figure 2. The findings highlight that nine materials are above the 0.1 wt% mass share (aluminum, chromium, copper, iron, magnesium, nickel, antinomy, tin, and zinc). In particular, as shown in Figure 2, these major materials for R3 account for 99.95% of the mass but 88.56% of the rarity. By comparison, the mass of the major materials for R4 total 99.82%, whereas the rarity accounts for 87.75%. The discrepancy in weighting between mass and rarity is seen clearly in Figure 2, where these 14 minor materials account for more than 11% and 12% of the total rarity of R3 and R4, but only 0.05% and 0.18% of the total mass. This highlights the increased importance and hidden value of rare materials when adopting a rarity assessment approach.

Examining the estimations in more detail, we observe large differences between the TR and mass values of a number of specific materials. For instance, regarding waste category R3, iron, which constitutes around 57% of the mass, translates to only 7.78% of the rarity. Additionally, antimony which is likely not recovered in this process, accounts for 13.44% of the mass, while it shows to account for 27.95% of the rarity. Losing roughly 28% of the rarity materials present in this stream is undesirable from a CE perspective, where addressing resource depletion is a major drive.

Such distinctions between mass and rarity become more acute when examining several materials whose mass share is below 0.01 wt% of the total of that product category stream (both for R3 and R4). For instance, while cobalt accounted for 0.0.121% of the mass in R3, its rarity was 0.569%. At the same time, indium accounted for 0.004% of the mass but 6.398% of the rarity. Both cobalt and indium are, among other materials, crucial to the energy transition due to their use in batteries (cobalt) and PV technologies (indium) (Bobba et al., 2020). Overall, the estimations indicate that the

TABLE 4 Estimated differences between mass and rarity at the company level

Company level							
R3				R4			
Elements	Mass	+/−	Rarity	Elements	Mass	+/−	Rarity
Fe (A)	57.3220%	−	7.7833%	Fe (A)	84.6112%	−	22.7317%
Cu (A)	13.7189%	+	20.3766%	Al (A)	8.2207%	+	45.8358%
Sb (A)	13.4356%	+	27.9455%	Cu (A)	4.4800%	+	13.1659%
Al (A)	9.6731%	+	27.2585%	Cr (A)	1.0243%	−	0.3534%
Mg (A)	3.7144%	−	2.3077%	Ni (A)	0.6353%	+	4.0621%
Zn (A)	0.9374%	−	0.7870%	Zn (A)	0.4907%	+	0.8151%
Sn (A)	0.7272%	+	1.4042%	Mg (A)	0.2190%	+	0.2692%
Cr (A)	0.2161%	−	0.0377%	Sn (A)	0.1341%	+	0.5124%
Ni (A)	0.2055%	+	0.6641%	W (B)	0.0993%	+	6.7211%
Co (B)	0.0121%	+	0.5691%	Sb (B)	0.0672%	+	0.2765%
Ag (B)	0.0119%	+	0.4548%	Co (B)	0.0061%	+	0.5662%
W (B)	0.0071%	+	0.2440%	Nd (B)	0.0040%	+	0.0224%
Bi (B)	0.0061%	+	0.0143%	Mo (B)	0.0031%	+	0.0274%
In (B)	0.0041%	+	6.3980%	Pd (B)	0.0019%	−	0.0007%
Mo (B)	0.0034%	+	0.0152%	Ag (B)	0.0017%	+	0.1266%
Nd (B)	0.0028%	+	0.0080%	Dy (B)	0.0005%	+	0.0031%
Au (B)	0.0013%	+	3.7150%	Au (B)	0.0005%	+	2.5143%
Pd (B)	0.0004%	−	0.0001%	In (B)	0.0003%	+	0.8799%
Dy (B)	0.0003%	+	0.0009%	Bi (B)	0.0001%	+	0.0003%
Li (B)	0.0001%	+	0.0003%	Li (B)	0.0001%	+	0.0004%
Tb (B)	0.0000%	+	0.0001%	Pt (B)	0.0000%	+	1.1154%
Pt (B)	0.0000%	+	0.0155%	Tb (B)	0.0000%	+	0.0002%

A, those elements above 0.1% of the total mass; B, those below.

relative rarity of certain materials within a waste stream, as expressed in exergy, shows large differences compared to their mass in the products. This mass and rarity discrepancy is similarly observed in the R4 estimations. The major bulk metals iron, copper, and aluminum account for 88.61%, 4.45%, and 8.22% of the mass present in this stream, respectively, compared to 22.73%, 13.17%, and 45.84% of the rarity. This result is relevant since all bulk metals are recovered in the primary recycling process, for example, copper, aluminum, and iron.

Examining the composition of WEEE from these two levels of the case study reveals several insights. Namely, aluminum, copper, and iron comprise the majority of the weight. The use of the TR indicates some large discrepancies, particularly between those materials below 0.1% of the mass. These account for 21% and 4.56% (national) and 11% and 12% (company) for R3 and R4, respectively. The difference between the mass and the rarity scores can be explained through the specificity of the case study sampling approach, which is not captured in aggregated reporting. Yet, the use of the indicator points to the increased significance of the minor materials in both levels of analysis, for example, indium, tungsten, cobalt, and lithium.

3.2 | Critical policy reflection

Currently, the EU WEEE Directive and its 2012 recast (EP & Council, 2002, 2012) recycling targets that affect the product categories studied include 70% and 55% recycling/reuse rate (by weight) for screens and monitors (R3), and small equipment and IT and telecommunications (R4), respectively. This section considers the effect these targets would have should the recovery requirements be based on mass or rarity. The purpose is to theoretically consider how the specific actors in WEEE recycling respond to—and fulfil—such targets, given the indicated policy context, and how, looking beyond this Italian case, what the implications of a rarity approach would be for decision-making processes in EU EoL policies.

Looking at the national level, the R3 70% recycling target could be met through recovering iron. However, meeting the targets through a TR perspective would require aluminum in combination with other elements. For R4, meeting the 55% target via mass could also be done by only

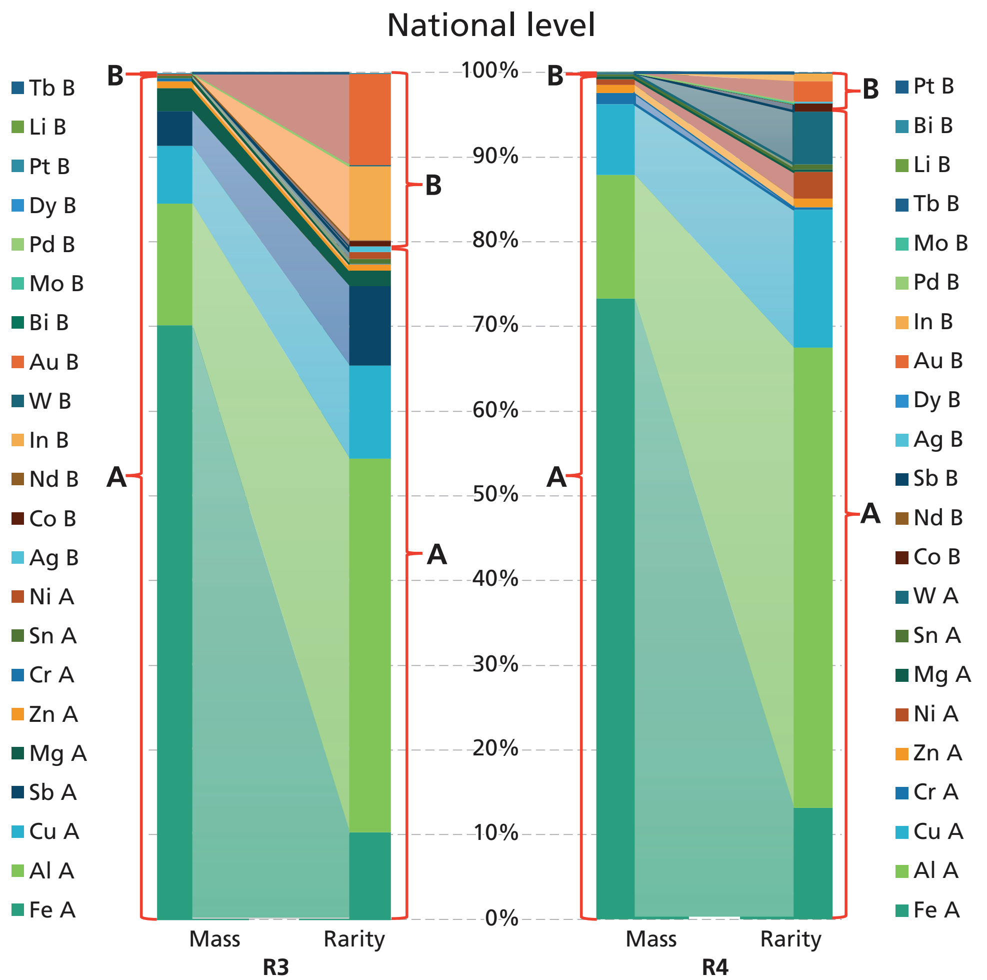

FIGURE 1 National level: (a) Mass and rarity for product categories R3 and R4 for metals with a mass share above 0.1 wt%. (b) Mass and rarity for product categories R3 and R4 for metals with a mass share below 0.1 wt%. Full names of the elements are provided in Table 2

TABLE 5 Meeting the EU recycling targets through either a mass or rarity approach (based on the national case study)

Product category and target	Mass %	Rarity %
R3 recycling 70%	Iron (70.2)	Aluminum (44.1), gold (10.7), copper (10.9), iron (10.3), indium (9.7), and antimony (9.3)
R4 recycling 55%	Iron (73.3)	Aluminum (54.3), tungsten (6,2), nickel (3.1)

recovering iron. However, a target based on TR would require recovering aluminum, with a combination of other element, for example, tungsten or nickel. Applying the indicator at the national level indicates the weightings between materials, and (a) signifies the significance minor materials have and (b) the varying combinations of specific materials that would need to be recovered should the targets considerate TR over mass (Table 5).

Applying the targets to the company level vary against the outcomes of the national. Starting with R3, the target of 70% recycling, based on the mass of materials, could be met by focusing on copper and iron. Yet, from a rarity perspective, meeting the targets would require focusing on a combination of aluminum, copper, and antimony. Alternatively, for R4, a target of 55% recycling can be met from a mass perspective by simply collecting iron. Alternatively, a rarity perspective would necessitate including aluminum, nickel, and CRMs tungsten (Table 6). These insights are comparable to Ortego et al. (2018b) for how the EPR policies would be effected should a TR approach be taken.

These suggestions do not consider the specific technical requirements to correctly recycle each element, which is likely to be demanding for small, highly concentrated materials. It also does not include questions of economic feasibility and market conditions, which often limit the introduction of novel recycling practices. Instead, it sheds light on the TR value (expressed in exergy) each of these elements has against their relative abundance in the Earth's crust and, crucially, it suggests issues of current and future accessibility for these particular materials. This is essential given the increasing demands for these materials and current supply risks for many (Bobba et al., 2020).

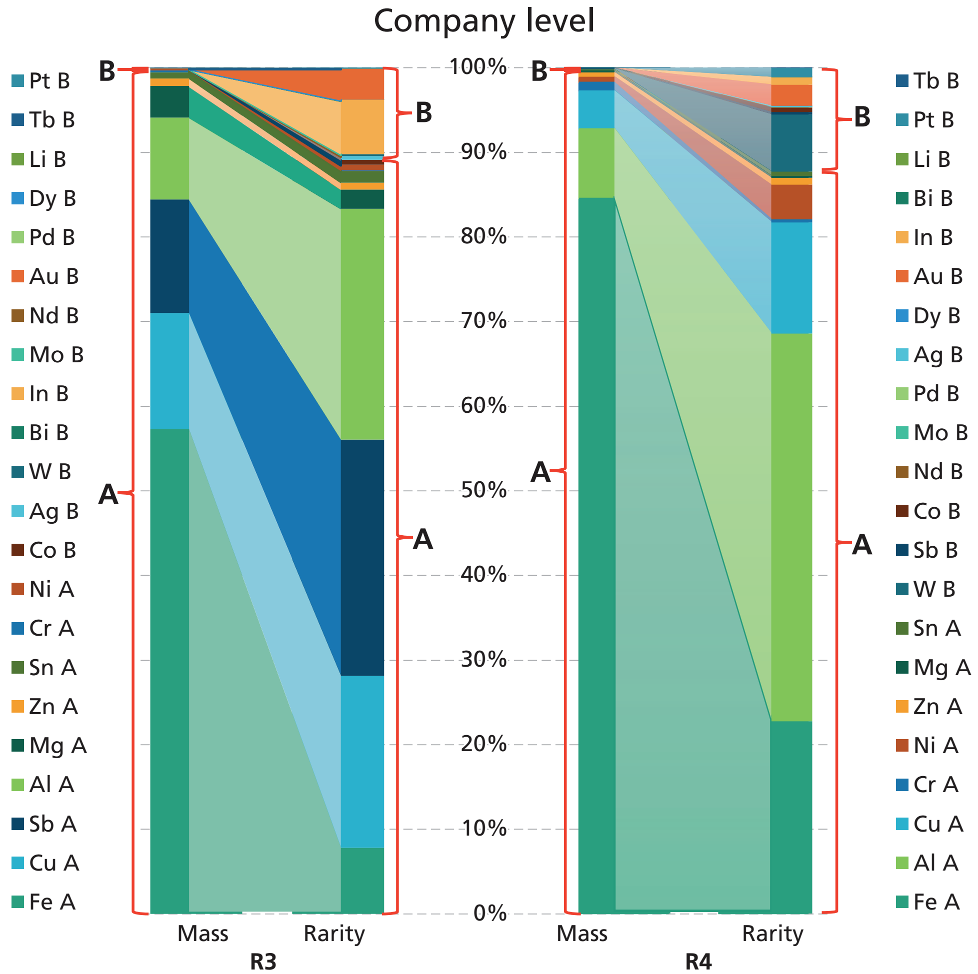

FIGURE 2 Company level: (a) Mass and rarity for product categories R3 and R4 for metals with a mass share above 0.1 wt%. (b) Mass and rarity for product categories R3 and R4 for metals with a mass share below 0.1 wt%. Full names of the elements are provided in Table 2; the underlying data for this figure can be found in Table 4.

TABLE 6 Meeting the EU recycling targets through either a mass or rarity approach (based on the company case study)

Product category and target	Mass %	Rarity %
R3 recycling 70%	Copper (13.7), iron (57.3)	Aluminum (27.2), copper (20.3), antimony (27.9)
R4 recycling 55%	Iron (84.6)	Aluminum (45.8), nickel (4), tungsten (6.7)

The results provide an opportunity to reflect on the broader policy regime for the CE of electrical products in the EU. We reflect on the TR estimations at the national and company level, on *how* the current policy regime affects certain actors' decisions, what policy and legal structures *could* be adjusted to accommodate this reality and the underlying pressures for the CE, for example, long-term resource depletion. Applying the TR indicator is not done to argue that national targets must be based on TR. Instead, it is used to illustrate the increased importance and significance (from a long-term perspective) that different materials have, particularly many CRMs (some of which are lost). The company case illustrates the challenge of accurate WEEE sampling and how the policy conditions can result in particular decision-making outcomes for the subsequent utilization and recovery of materials, a value retention system that prioritizes mass at the expense of rarity and scarcity (Campbell-Johnston et al., 2020).

The first point of contention is the nature of the EPR targets. Whilst there is a clear logic (both policy and market wise) in focusing on mass-based targets, the (unintended) consequence, as illustrated in this study, is the loss of materials that are either critical or geologically scarce, for example, 38% TR loss for R3 and 10% R4 (see Section 3.1). This is a more fundamental issue. CE policies should intend to retain materials that are likely to be exhausted or otherwise inaccessible in the not so distant future (Henckens et al., 2016a). Following the implications of our insights, and in line with other authors (Arduin et al., 2020), we propose the need for EPR policies to recognize the issue of critically and geological scarcity, either in the monitoring or target setting. For this, TR could be a useful indicator to support the decision-making process for target or recycling standard setting, as it indicates the hidden (exergy) value of different materials. TR can help assist in identifying CRMs that are worthy of consideration for developing recycling processes and policy around.

In addition, two critical issues that emerged during this research were: (a) obtaining data on the composition of products in a specific waste stream and (b) understanding the quantities of critical and scarce materials within those products. These are issues already known in the field of EPR (see Huisman et al., 2017), that were reconfirmed. The first issue highlights the challenge of understanding the actual complexity of WEEE streams arriving at processing facilities, which has implications both on their ability to process them, and the efficacy of EU policies aimed at reducing those streams. For the second issue, at present, current eco-labeling requirements and product category declarations do not require acknowledging the presence and quantities of such materials, further obscuring the knowledge on what materials, including CRMs, are moving through the market and the processing facilities. This could be supported by expanding the reporting requirements included in the Waste Framework Directive (2018) for the European Chemicals Agency for producers to report CRMs quantities. This is currently done for specific products, for example, computer servers, but not all. Policymakers should use this information for long-term target setting and innovation and R&D policy for CRMs recovery. Producers are already required to register several hazardous substances, for example, lead, cadmium, and mercury, which include several CRMs, for example, cobalt and antimony under the REACH Directive. The requirements should also extend to all CRMs. For eco-design, increasing the accessibility of information on the presence of such materials (for policymakers and recyclers), or, working toward substitutions where either recovery or increased accessibility is recommended. The policy implications of this research have been more comprehensively outlined in Campbell-Johnston et al. (2022).

3.3 | Limitations

This approach provides novel insights into the quantities of materials with the WEEE streams. The estimations of this study allow us to consider the limits of policy and usefulness of the indicator. However, we acknowledge the methodological and data gaps and uncertainties. First is the issue of WEEE sampling and characterization. It is widely known that the reporting of WEEE data in the EU is characterized by many discrepancies and inconsistencies (Forti et al., 2018). Multiple variables effect WEEE over time, from the product types to the material composition. The reporting at the company involved batch tests of products, which was then scaled up to the quantities of materials entering the facilities allowing for an estimate at to whether the recycling targets were met. We opted for our sampling strategy, not for representativeness (a general issue with WEEE reporting), but to illustrate the types of products and the application of the indicator at the company level as no other data was available to us. Estimates of the elemental composition of products in the samples and those at the national level were made using the best available data (Huisman et al., 2017). Since the underlying data and the data for the TR were not directly accessible to us, it was not possible to conduct sensitivity analyses around the macro estimations in the present work. The micro estimations could have been strengthened by conducting lab tests on the products sampled to more accurately document their elemental composition. However, such a means was not available. The TR assessment was calculated having these limits in mind. Strengthening the reporting requirements and composition of products and WEEE streams coupled with greater stakeholder collaboration between producers, policymakers, and recyclers is necessary to improve the potential for CRMs recovery.

Another limitation relates to the scope in which the TR indicator was applied. As outlined in the methodology, this research did not consider the specific chemical composition of each product and technical processes needed to recover individual CRMs and how this relates to TR values. This work is being explored by Valero and Valero (2020) but was not possible within this study meaning the focus was more at the aggregated elemental level. Improving the methodology and extending its application would require an adaptation of exergy databases proposed by Ortego et al. (2018b) and information on energy requirements and resources consumed during the treatment of and the recovery of CRMs, dividing the contribution directly linked to materials and to extraction and treatment processes. Currently, information such as exergy efficiencies of the processes or technologies used is not usually available such as the exergy cost of the mechanical or manual dismantling process. As such, the proposed indicator was applied to the main CRMs included in the WEEE sample. The required calculations were performed directly by the authors using exergy data provided in the Supporting Information.

Finally, we used the indicator to suggest potential policy implications based on the TR findings. We do not seek to generalize the results to the EU, instead to use the indicator to reflect on the outcomes of the policy context, and, based on the insights how this context could be modified. However, in setting CRMs targets and conditions, broader issues must be considered, namely, the socio-economic and environmental considerations, for example, energy requirements, that TR does not consider. Similarly, market and technical dynamics for EoL materials, which greatly influence the recovery process, are not a part of the rarity assessment and should be studied separately. The commercial extraction of specific rare elements and materials is more promising for some due to the combination of favorable market conditions, collection practices and technological advancements (see CEWASTE, 2021).

4 | CONCLUSION AND RECOMMENDATIONS

In conclusion, growing demand for specific materials will cause increased depletion and scarcity risks. Consequently, understanding which materials are most important from a long-term perspective, particularly those at the EoL as higher recycling is needed to offset future demand bottlenecks for specific materials. This research used the TR indicator applied in a novel context to theoretically explore the differences between the mass and rarity of materials within WEEE streams. Using the case of Italy, it examines two product categories comparing the estimated mass and rarity balance at the national level. This was further explored at the company level to illustrate the complexity and discrepancies of the policy context and the application of the indicator. This study takes a unique interdisciplinary and exploratory approach that connects a technical exergy approach with a reflexive policy analysis.

The results of the company analysis indicate that the recycling process prioritizes the recovery of mass and bulk metals at the expense of minor and critical ones. A general observation is that the primary recycling process recovered three mass metals (aluminum, iron, and copper). Based on estimates of potentially subsequent recycling operation, the results infer that around 13 materials are lost in this process. Of these materials that are lost, three are categorized as CRMs by the EU (European Commission, 2020). Using this indicator revealed a large difference between the mass and rarity of specific materials. For example, for the product category R3, iron accounted for 57% of the mass compared to 7% of the rarity. Whilst indium accounted for 0.004% of the mass but 6.398% of the rarity. This difference becomes significant when the issue of rarity is applied to the current EU EPR WEEE recycling targets. Using TR in an explorative manner allows us to consider the varying implications of EU policy, and how, in the hypothetical situation rarity was used, what the implications would be.

This explorative analysis provides a point of reflection on the limitations of EPR within the EU policy regime. In our sample, we estimate up to 38% of the TR of one product category is lost. The logic of CE argues for closing material and energy loops to maintain the value of products and materials. Here we illustrate the potential for a value retention orientation that accurately includes the issue of rarity and criticality, from which, we argue, TR could be a complementary indicator to help the decision-making process for both target and standards setting. For example, in highlighting CRMs worthy of attention in future recycling processes and policy. However, further research in the application of TR is needed to substantiate this. Moreover, based on the challenges of this research, there is a need for greater knowledge of the composition of products, including their CRMs, to be known by policymakers in order to help foster longer-term recovery and innovation options. Electronic products and electronic waste are projected to increase substantially in the coming decades. Thus, prospectively grappling with this question of criticality within the policy domain is essential.

Future research on TR should address two areas. First, this research has resulted in insights gained from applying the indicator in a novel case study context. Expanding the scope of this study to more companies and the EU more broadly, would result in more generalizable results. Second, research should compare the TR of elements with the exergy needed to recover it. This is proposed by Valero and Valero (2020) and is in the initial stages of being empirically explored (Torrubia et al., 2022). Focusing on the chemical composition of specific products would verify the practical applicability of the indicator. We further recommend that the socio-economic and environmental trade-offs between CRMs recovery and their associated environmental impacts (or benefits) are investigated in further research. This could be done by exploring how (thermodynamic) rarity could be integrated or contrasted with other assessment methods, for example, ones that account for broader geopolitical factors, to inform *which* materials are prioritized for recovery, for example, developing a multi-criteria decision analysis framework for EoL CRM policy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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NOTES

[1] These include geopolitical issues, for example, country origins of specific materials. In this research, we do not examine the socio-economic constraints on CRMs use and recovery, but focus on the issue of geological availability.

[2] This indicates the percentage of materials not sent to landfill. This information is sent to national and EU reporting agencies. This number does not include further losses at subsequent processes stages.

[3] In the dataset, the composition of certain products was based on scientific literature, not lab studies, see Huisman et al. (2017).

[4] In the dataset, the years 2016–2020 are all projected data, based on projected market shares. We decided that as the focus of this research is on the usefulness of the thermodynamic rarity indicator, using projected data was acceptable, as it was also done to complement the more detailed company-level data.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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