EL-KRETSEN

STENA CIRCULAR CONSULTING

HARVESTING CRITICAL RAW MATERIALS FROM ELECTRONICS AND BATTERIES

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PROJECT REPORT / FEBRUARY 2023

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EXECUTIVE SUMMARY

1 Background

- Critical raw materials (CRMs) play a vital role in Europe's economy. With growing concerns about the stability of future supplies, recent and upcoming EU legislation highlights the importance of improving the domestic capacity for CRM recycling and reuse
- In light of these developments, El-Kretsen is proactively seeking to understand the CRM content in WEEE and waste batteries, and whether there is a potentially viable business case for increasing the use of secondary CRMs beyond current practices

2 Key findings & opportunities

- The selected CRMs are primarily present within six components in the WEEE and battery waste stream: Printed circuit boards, NdFeB magnets, portable batteries, LED lights, LED displays, and solar PV panels
- The mass and value of CRMs within the identified components are expected to be relatively stable between 2022 – 2030, except for cobalt (+165%) lithium (+285%), and silicon (+770%)
- Amongst the components, printed circuit boards, magnets, and batteries stand out with the highest mass and value of CRMs. For 2022, they are estimated to represent 99.9 wt. % and 99.4 % of the monetary value[1] for the identified CRMs
- Magnets and batteries show potential for closed-loop recycling through improvements in detection, sorting, and separation. However, for printed circuit boards, the CRMs become part of the slag produced during metal refining, limiting the feasibility of material recycling
- The market analysis reveals that investments in EoL management are currently hindered by fluctuating market prices and geographical concentration of processing capacity. However, the anticipated growth in demand and changing policy landscape suggests that it is highly relevant for El-Kretsen to proceed with further analysis of the reuse and recycling of magnets and portable batteries

3 Recommendat-ions

El-Kretsen is recommended to:

- Conduct feasibility studies for NdFeB magnets and portable batteries. The scope of such studies should include the identification of suitable technologies for detection, sorting, and separation, and the assessment of their financial viability
- Advocate for policies that incentivize better EoL management of CRMs in WEEE components currently lacking a positive business case
- Enhance CRM recycling conditions by working with member organizations on product labelling and design for disassembly

SOURCE: SCC

[1] Estimate based on primary CRM values

ABBREVIATIONS

General	
CE	Circular Economy
DfC	Design for Circularity
DfR	Design for Recycling
EoL	End of life
EPR	Extended Producer Responsibility
ESPR	Eco-design for Sustainable Products Regulation
PMR	Precious Metal Recycling
SCC	Stena Circular Consulting
WEEE	Waste from electronic and electrical equipment
EEE	Electronic and electrical equipment
CRM	Critical raw material
EPA	Environmental Protection Agency
PCB	Printed circuit board

NdFeB	Neodymium-ferrite-boron	Dy	Dysprosium
NiMH	Nickel-metal-hydride	Gd	Gadolinium
LCO	Lithium-cobalt	Sm	Samarium
NMC	Nickel-manganese-cobalt	Ce	Cerium
NCA	Nickel-cobalt-aluminium	Ga	Gallium
HDD	Hard disk drive	B	Boron
		Pd	Palladium
Materials		Mn	Manganese
Ni	Nickel	Ng	Natural graphite
Cd	Cadmium	PGM	Platinum group metals
Li	Lithium		
Co	Cobalt		
REE	Rare earth elements		
Nd	Neodymium		
Pr	Praseodymium		

BACKGROUND

CRITICAL RAW MATERIALS ARE GAINING ATTENTION FOR THEIR VITAL ROLE IN A RESILIENT ECONOMY AND THE GREEN TRANSITION

Critical Raw Materials – a definition

- The assessment of critical raw materials is based on the **supply risk** and **economic importance** of a given material in the EU. The supply risk is based on multiple factors, such as the degree of supply concentration, import reliance, governance risks, and availability of substitutes
- Raw materials are deemed critical if they have **high importance** for end-use applications, **substitutes are scarce**, and there is a considerable risk of **supply shortage**
- The degree of criticality can **change over time** due to several factors (e.g., market shifts). Criticality assessments at an EU level are performed every three years
- The most recent **EU listing** includes 34 critical raw materials

Many of the critical raw materials are essential for the green transition

Examples of applications

Wind turbines

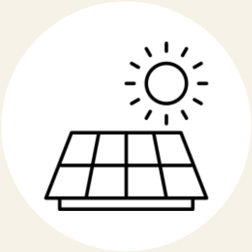
Rare earth elements (magnets), boron, silicon metal, manganese, nickel, copper, aluminium

Li-ion batteries

Lithium, natural graphite, cobalt, manganese, nickel, copper, aluminium

Heat pumps

Rare earth elements (magnets), boron, silicon metal, manganese, nickel, copper, aluminium



Solar photovoltaics

Gallium, boron, germanium, silicon metal, nickel, copper, aluminium

SOURCES: EC, Study on the critical raw materials for the EU (2023); EC, Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study (2023)

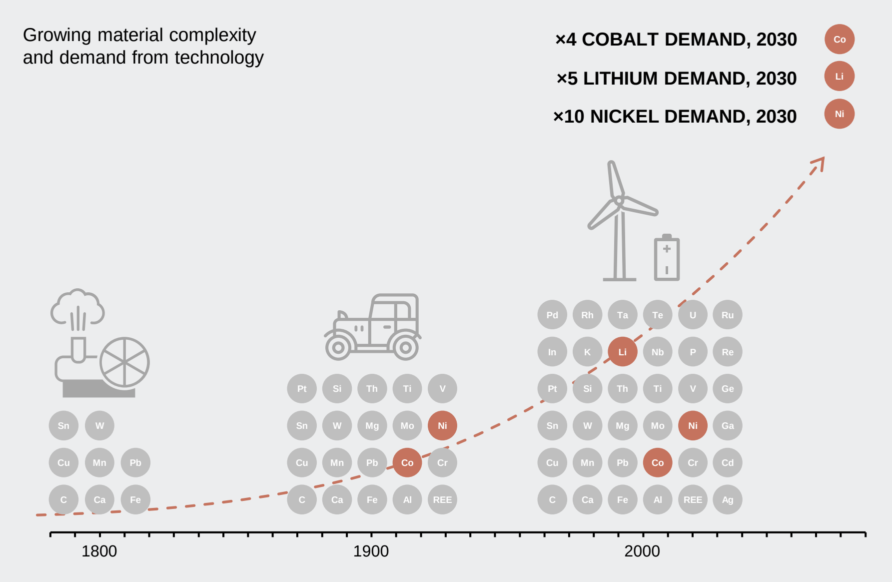
TODAY, MATERIAL RECYCLING OF MOST CRMS IS NOT COMMON PRACTICE, AND THE REUSE OF EOL COMPONENTS REMAINS LIMITED

	Barriers to material recycling	Barriers to product and component reuse
Market	▪ Volatile and low prices of strategic critical raw materials ▪ Lack of established market for recycled materials	▪ Producer resistance (concern for brand reputation, risk of cannibalizing) ▪ Consumer attitudes related to reliability, safety and aesthetics ▪ Limited availability of spare parts
Technological	▪ Lack of recycling technologies on a commercial scale ▪ Metallurgical limits of the recycling process	▪ Lack of solutions for traceability and identification of products and components ▪ Lack of solutions for quality assurance
Product	▪ Complex product design hinders efficient separation ▪ Insufficient transparency of CRM content ▪ Low and declining CRM content in EEE and batteries	▪ Heterogenous product design and lack of standardized components ▪ Obsolescence of parts and software
System	▪ Design of collection and recycling system for the efficient recycling of high-volume metals, e.g., aluminium, copper, and iron	▪ Unsuitable collection infrastructure leading to product damage ▪ Tax on chemicals in electronic goods
	No business case for recycling most critical raw materials	**Reuse is limited to high-value items in good condition**

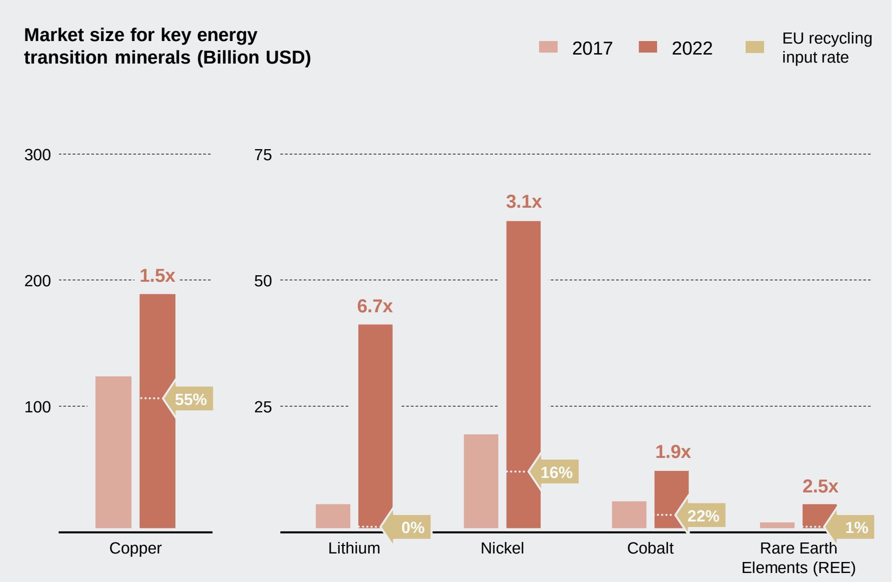
SOURCE: Trinomics, Emerging Challenges of Waste Management in Europe (2020); Junestedt et al., Förutsättningar för en ökad återvinning av kritiska råmaterial i Sverige (2023); Cole, Assessing barriers to reuse of electrical and electronic equipment, a UK perspective (2019); Expert interviews; SCC analysis

HOWEVER, THE SURGE IN DEMAND FOR CRMS IS CAUSING CONCERN ABOUT THE FUTURE SUPPLY…

The transition to green energy require advanced technologies and critical raw materials, which are limited in supply



The market size for certain CRMs has doubled in the past five years due to a combined increase in price and demand, highlighting the need for improved recycling to stabilize supply



SOURCE: Achzet, B. et al. Materials Critical to the Energy Industry: An Introduction (2014); IEA, Critical minerals market review, 2023; EC, Study on the critical raw materials for the EU (2023); SCC analysis

…. AND NEWLY ADOPTED AND UPCOMING LEGISLATION IS PUSHING FOR INCREASED CIRCULATION AND RECOVERY OF CRMS

The **new battery directive** mandates the recovery and reuse of battery materials

Key requirements for portable batteries:

- **Collection targets** for batteries: 45% by 2023, 63% by 2027, and 73% by 2030
- **Recycling efficiency targets:** 80% for NiCd batteries, 65% for Li-based batteries, and 50% for other types of batteries by 2025
- **Product design requirements:** Portable batteries to be removable and replaceable by the consumer by 2027

The **proposed CRM Act** aims to increase EU:s self-sufficiency in critical raw materials[1]

Key proposed initiatives:

- Benchmarks for **domestic capacities** for strategic CRMs to be reached by 2030, including at least **25% of the EU's annual consumption for recycling[2]**
- Strategic initiatives for **collection, reuse and recycling** of high CRM **content** products and waste streams
- **Labelling requirements** of products with permanent magnets > 0.2 kg
- Post 2030 requirement on min. % of **recycled CRM content** in permanent magnets (likely magnets > 0.2 kg)

The proposed ESPR establishes stricter circularity and information criteria for products

Key proposed initiatives:

- Framework for **ecodesign requirements** and **digital product passport** to trace, share and compare key product information
- Product design requirements to **aid material recycling,** such as design for disassembly and recyclability
- It currently **lacks specific CRM requirements**; however, the Swedish EPA has recommended the Swedish government push for the disclosure of CRM content in product passports

The legislative landscape is increasingly pushing for improved EoL management of CRMs through building domestic capacity and mandating circular product design

1. A detailed overview of the CRM Act is found on page 38 in the Appendix B. 2 Revised from 15 to 25 % in a provisional agreement reached by the EU council and parliament. SOURCE: Regulation (EU) 2023/1542 concerning batteries and waste batteries; COM/2023/160 final, Proposal Critical Raw Materials Act 3; COM/2022/142 final, Proposal Ecodesign for Sustainable Products Regulation; EU JRC, Ecodesign for Sustainable Products Regulation - preliminary study on new product priorities (2023); Naturvårdsverket, Ökad återvinning och återanvändning av elutrustning (2023)

EL-KRETSEN WOULD LIKE TO UNDERSTAND THE IMPLICATIONS AND OPPORTUNITIES OF THIS DEVELOPMENT FOR EPR ORGANIZATIONS

The project aims to assess the opportunity for improving reuse or recycling of CRMs in the EoL system for WEEE and waste batteries

Project Inquiries	Activities	Actions
Which EEE and Battery products contain CRMs, of which type, and in what quantities?	1 **Mapping CRM usage and content in EoL EEE and Batteries on the Swedish market**	▪ Analysis of existing CRM volumes to identify relevant product categories ▪ Development of future scenarios for CRM volumes in the reuse and recycling system ▪ Selection of key product types for improved EoL management of CRMs
Is there a potentially viable business case for improving the use of secondary CRMs beyond current practices?	2 **Assessing the theoretical business opportunity for secondary CRMs**	▪ Market analysis for selected CRMs, considering the anticipated impact of upcoming legislation ▪ Financial assessment to discover the potential business opportunity ▪ System mapping to identify key stakeholders and draft points of intervention

The project findings will serve as the groundwork for future feasibility studies aimed at enhancing EoL management

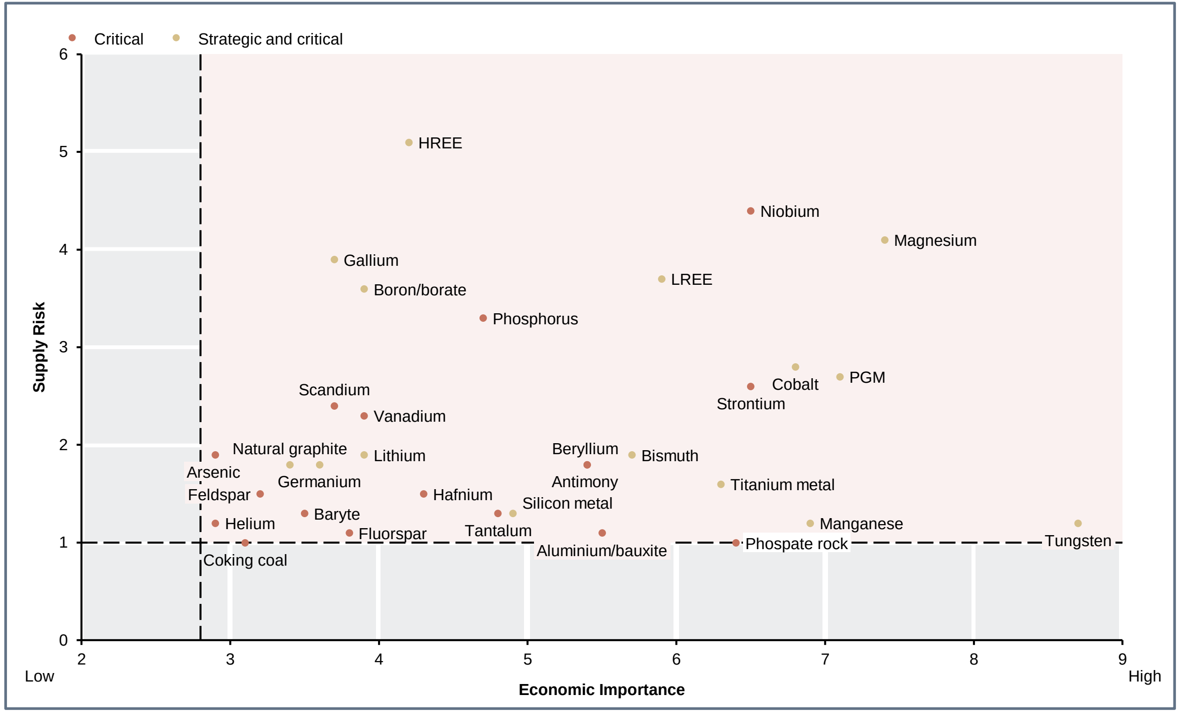
SOURCE: SCC

PROJECT SCOPE AND APPROACH

AMONG THE CRITICAL RAW MATERIALS, SOME ARE IDENTIFIED AS STRATEGIC AND ARE THE FOCUS OF THIS PROJECT

Strategic and critical raw materials

- **Strategic raw materials are a subset of CRMs** essential for technologies within the green transition, digitalization, and the defence and space industries, where forecast demand risks outstrip supply
- **There are fifteen materials and groups of materials** that are classified as strategic and critical[1] by the proposed CRM act. Groups of materials include PGM[2] and Heavy and Light Rare Earth Elements (HREE, LREE) for magnets[3]
- **Material recycling of strategic CRMs is limited**. Only five out of all critical and strategic materials have ≥10 % of the material supply from recycled scrap



1. Copper and nickel are classified as strategic but not critical, thereby excluded from the scope; 2. Ruthenium, rhodium, palladium, osmium, iridium, and platinum; 3. Neodymium, Praseodymium, Terbium, Dysprosium, Gadolinium, Samarium, Cerium

SOURCE: EC, Study on the critical raw materials for the EU (2023)

THE PROJECT ADOPTS A FUNNEL APPROACH TO GENERATE INSIGHTS AND DEVELOP RECOMMENDATIONS FOR EL-KRETSEN

The approach involved five main steps which enabled a systematic and continuous prioritization of materials and components

	Project step[1]	Output
1	Identification of which components are most likely to contain CRMs	Selection of six components to investigate further
2	Mapping of the CRM content of each component	Reduced nr of CRMs in scope based on presence within EEE and batteries
3	Estimation of the average concentration of CRMs for each component	Reduced nr of CRMs in scope based on availability of data
4	Estimation of the future EoL mass of components and CRMs, including assessment of CRM value	Prioritization of three components and six CRMs for market analysis
5	System mapping to identify points for intervention	Prioritization of two components for the next steps

Prioritization of two components containing 10 different CRMs for improved EoL management

[1]A more detailed description of the project steps is found on page 41 of the methodology section

SOURCE: SCC

ANALYSIS AND FINDINGS

EXAMINING CRITICAL RAW MATERIALS IN BATTERIES AND EEE REVEALS THEIR PRIMARY PRESENCE WITHIN SIX COMPONENTS

The WEEE and battery waste flow exhibit high heterogeneity and an uneven distribution of CRMs. Most CRMs are commonly found within six key components, which are prioritized in this project

Table: Overview of the selected CRMs per component

Component	B	Ga	Pd	Co	Si	Mn	Ng[1]	Li	Nd	Pr	Dy	Gd	Sm	Ce
PCBs			■	■					▨	▨	▨	▨	▨	▨
Batteries				■		■	■	■	■	■				■
c-Si PV panels	▨	▨			■									
LED lights		■		▨										▨
LED display		▨										▨		▨
Magnets	■	■		■					■	■	■	■		

■ Present in component ▨ Present in component, low concentration (<0.1W%)

The presence of the chosen CRMs within each component are as follows:

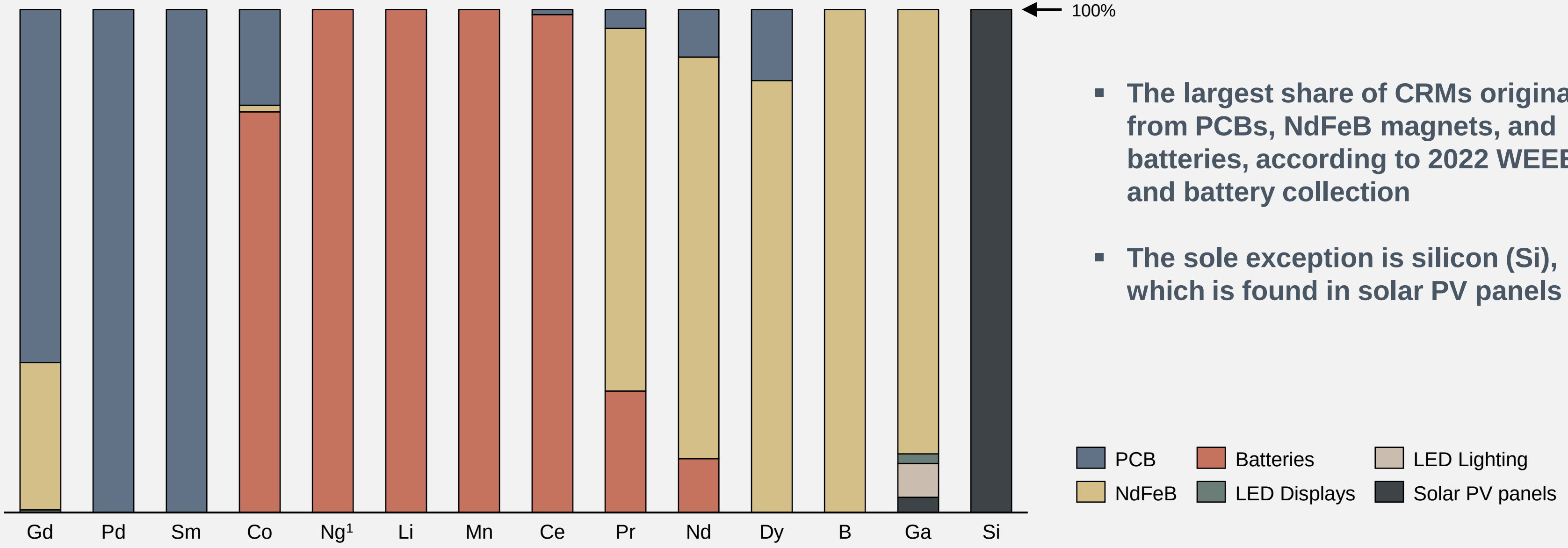
- Printed Circuit Boards (PCBs) provide a platform for electronic components,[2] containing most of the CRMs
- Portable batteries encompass various CRMs, depending on type and chemistry, in the cell electrode and the electrolyte
- c-Si photovoltaic panels use solar cells which contain Si as semiconductor material doped with small amounts of Ga or B, with the latter being phased out
- LEDs contain Ga as a semiconductor material, largely replacing the prior use of Ge. REEs are present in the phosphor coating as a luminescent substance
- NdFeB magnets are composed of an Iron Nd and B-alloy. The use of other CRMs depends on the application

1. Natural graphite; 2. Examples include integrated circuits (ICs), chips, connectors, contactors, capacitors, inductors, and diodes.

SOURCE: Norden, Critical metals in discarded electronics (2016); SCC analysis

MOST OF THE CRMS ARE USED FOR SPECIFIC APPLICATIONS AND CONCENTRATED TO ONE OR A FEW OF THE COMPONENTS

Share (%) of each material per component based on the collected WEEE and portable waste batteries in Sweden, 2022



- **The largest share of CRMs originate from PCBs, NdFeB magnets, and batteries, according to 2022 WEEE- and battery collection**
- **The sole exception is silicon (Si), which is found in solar PV panels**

1. Natural graphite

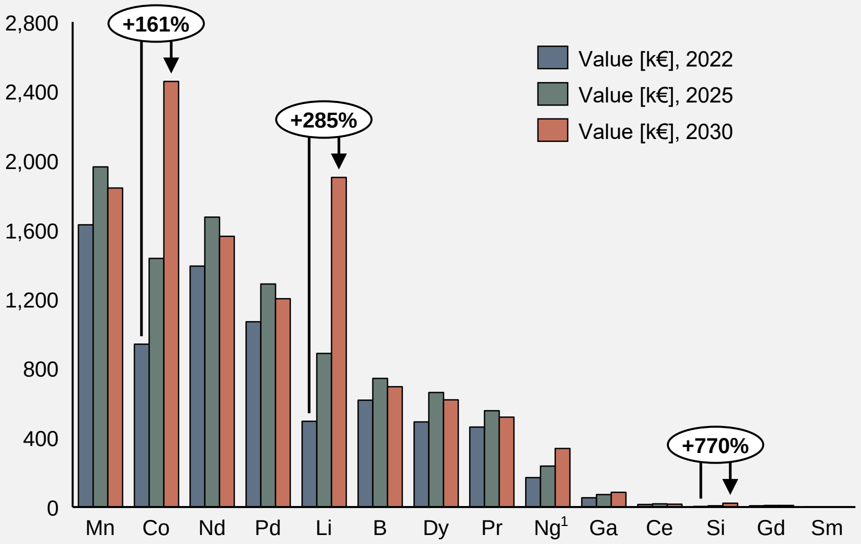
SOURCE: SCC analysis

STENA RECYCLING

THE CURRENT AND PROJECTED FINANCIAL VALUE OF THE MATERIALS INDICATES WHICH ONES HAVE A STRONGER BUSINESS CASE POTENTIAL

The value of materials found in batteries will increase exponentially due to increased collection of Li-ion batteries

Graph: Value of estimated mass of the selected CRMs in WEEE and waste batteries



The value is influenced by waste collection rates, CRM concentration, and primary material value

- Manganese (Mn) represents the highest value in 2022 due to a high wt.% and mass of EoL alkaline batteries. Li-ion and NiMH, with lower wt.% of manganese, are not expected to greatly impact the future value
- The potential value of cobalt (Co) (165%) and lithium (Li) (285%) will rapidly rise as Li-ion battery collection catches up to sales
- Neodymium (Nd) and praseodymium (Pr) maintain a relatively high and stable value through 2022, 2025, and 2030, driven by high material prices and widespread use of NdFeB magnets in EEE. A slight decrease is expected by 2030 due to an overall decline in collected WEEE tonnage
- Silicon (Si) exhibits the most significant value increase (+770%), driven by the expansion of solar PV stocks and the subsequent rise in failed panels (0.05% failure rate), yet the value remains insignificant. A substantial accumulation of EoL panels is anticipated to occur post-2040

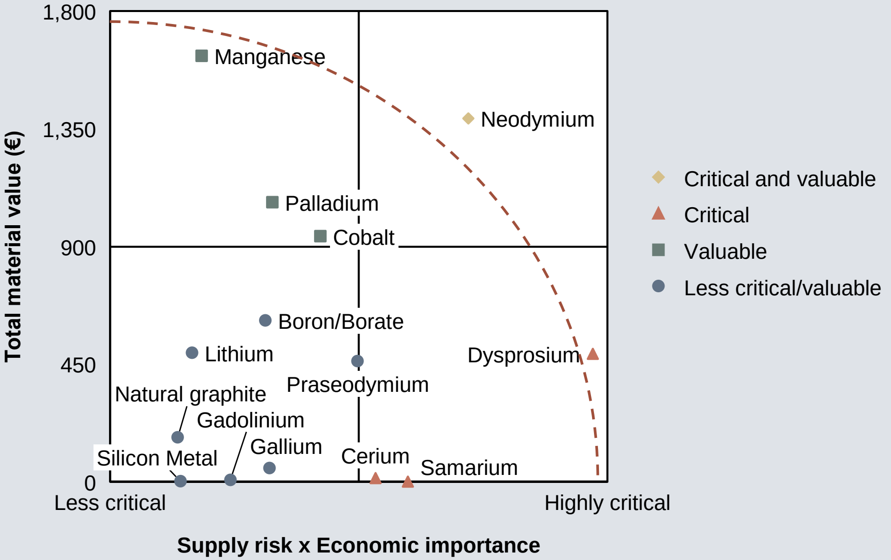
Disclaimer: The estimate of current and future material value is approximate and relies on primary material values from 2023-2024. The varying prices of critical raw materials, influenced by political objectives and changing demand patterns, present challenges in accurately estimating future material values

1. Natural graphite

SOURCE: SCC analysis

WHEN ADDING THE LEVEL OF CRITICALITY TO THE ANALYSIS, THE CRMS MAINLY FOUND WITHIN BATTERIES AND MAGNETS STAND OUT

CRMs mainly found within batteries (Mn) and magnets (Nd, Dy) score the highest on value and criticality



- Manganese (Mn) holds the highest overall material value, making it financially relevant despite a lower criticality score
- Neodymium (Nd) stands out with the highest combined material value and lower criticality, warranting further examination
- Dysprosium (Dy) scores highest on criticality, underscoring the EU's need to secure a sufficient supply
- Additionally, Cerium (Ce) and Samarium (Sm) show relatively high criticality, but their material value suggests recycling efforts may not be viable
- While materials in the lower-left corner showcase lower value and criticality on their own, they may be considered in efforts to improve EoL handling if they can be recovered or preserved alongside other materials

SOURCE: EC, Study on the critical raw materials for the EU, 2023; SCC analysis

FOR SIX OF THE CRMS IN BATTERIES AND MAGNETS, THE SUPPLY CHAIN IS MAINLY OUTSIDE THE EU, AND RECYCLING IS WELL BELOW THE TARGET

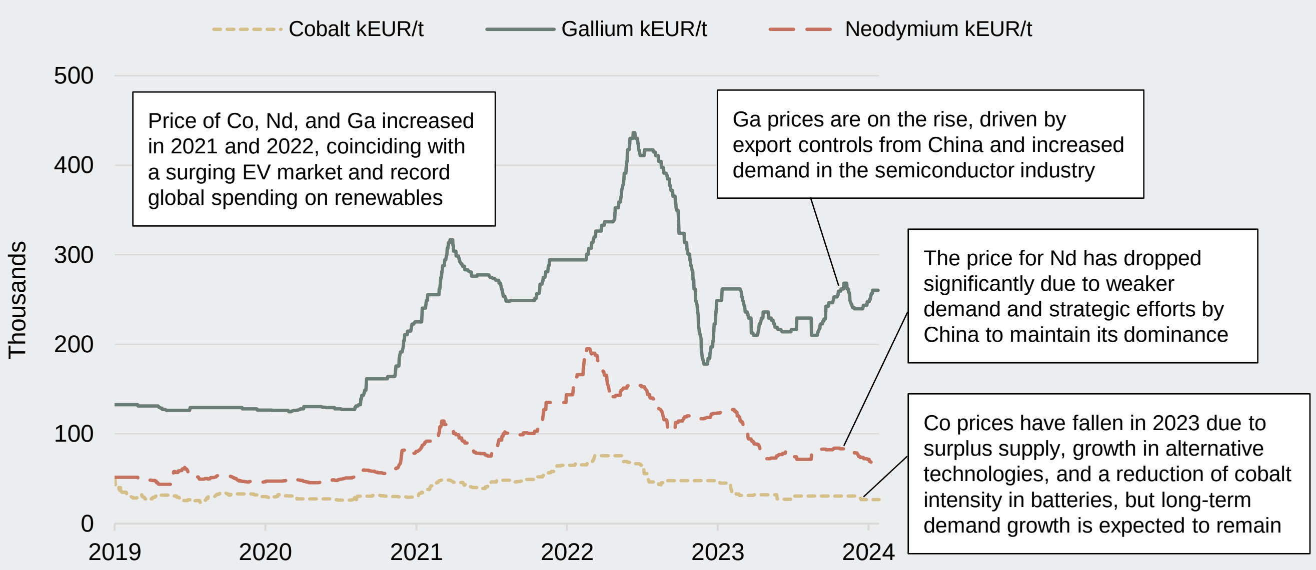
Material	Main application in electronics	Extraction capacity	Processing capacity	EoL-RIR[1]
Neodymium	Permanent magnets	China (68%), Australia (10%), US (9%)	China (85%), Malaysia (11%)	1% (LREE)
Dysprosium	Permanent magnets	China (84%), Myanmar (9%), Russia (2%)	China (100%)	1% (HREE)
Cobalt	Li-ion batteries (LCO, NCA, NMC), integrated circuits, permanent magnets	DRC (60%[2]), Zambia (8%), Russia (4%)	China (60 %), Finland (11%)	22%
Manganese	Alkaline and NiMH batteries	South Africa (29%), Australia (16%), Gabon (14%)	China (58%), India (13%), Ukraine (4%)	9%
Gallium	Dopant and semiconductor material in PV panels, integrated circuits, LED displays/lights	N/A. Ga is primarily extracted from smelting bauxite into aluminium	China (94%), Ukraine (2%), Russia (2%)	0%
Boron	Integrated circuits, capacitators, batteries, permanent magnets	Turkey (48%), US (25%), Chile 11%)	Turkey (45%), US (23%), Chile (10%)	1%,

- Meeting the proposed benchmarks on 25% domestic recycling of CRMs by 2030 will necessitate substantial developments in recycling and processing capacity
- Today, the EU lacks extraction capacity for the analyzed CRMs, and most processing capacity is concentrated in China, allowing them to set the global prices of these materials
- Cobalt is most closely aligned with the proposed benchmark on recycling capacity, with an EoL-RIR of 22 %. However, closed-loop recycling is inhibited by material downcycling, losses and exports

1. Ratio of recycling from scrap to EU demand for material in the manufacturing stage; 2.China owns 70 % of the capacity in the DRC
SOURCE: EU JRC, Material System Analysis of five battery-related raw materials (2020); EC, Study on the critical raw materials for the EU (2023)

THIS MAKES THE RISK OF EXTERNAL DISRUPTIONS HIGH, AND THE MATERIAL PRICES ESPECIALLY HARD TO PREDICT

Graph: Historic prices for selected virgin CRMs



Disclaimer: Dysprosium, boron (high-purity), and manganese (high-purity) are excluded due to a lack of historical data

- The price volatility of the analyzed materials can be attributed to three main factors: technological advancements, shifting demand, and **external disruptions**
- The external disruptions **stem from political interventions** and **other abrupt** supply changes
- The risk of external disruptions **escalates with a geographically concentrated supply chain**, introducing uncertainty into investment in EoL management of numerous CRMs

SOURCE: Trading economics (2023); IEA; Key market trends (2023); Reuters, Rare earths prices sink to lowest since 2020 as China ramps up supply (2023); Reuters, China export curbs choke off shipments of gallium, germanium for second month (2023); IEA, Announcement on the Implementation of Export Control of Items Related to Gallium and Germanium (2023), Fast markets, A make-or-break year for non-Chinese gallium market (2023)

HOWEVER, THE GREEN TRANSITION IS A MAJOR DRIVER OF FUTURE DEMAND FOR SOME CRMS; SUGGESTING A LONG-TERM VALUE INCREASE

Material	EU demand 2020 (t/yr)	Global demand increase 2030[1]	Global demand increase 2050*	Main technology	Impact on global demand[2]
Neodymium (Nd)	1 103	1.8 – 4.1x	4.9 - 10.9x	Wind turbines, traction motors	High
Dysprosium (Dy)	126	1.4 – 4.5x	3.2 - 12.8x	Wind turbines, traction motors	High
Cobalt (Co)	8 620	6.5 – 8.8x	17.4 –17.9x	Batteries	High
Gallium (Ga)	6	1.2 – 1.7x	16.2 –26x	Solar PV, ICT	High
Boron (B)	145	1.2 – 2x	1.9 – 3.2x	ICT, Solar PV	Low
Manganese (Mn)	16 823	1.7- 3.2x	4.3 – 6.2x	Wind turbines, batteries	Low

Nd, Dy, Co, and Ga are most impacted by the green transition and digitalization

- Nd and Dy demand is driven by their use in permanent magnets, with a global material supply shortage anticipated by 2030
- Co demand is expected to outstrip supply by 2030, even when considering the shifts in battery chemistry and technology
- Ga demand from the renewable energy sector is expected to surpass 100% of global supply by 2050
- B and Mn are expected to be less affected by the green and digital transition, with global demand from the sectors representing <1% of the supply in 2020. This is because high-purity B and Mn are mainly used, which makes up only a small part of the overall material supply
- In conclusion, the demand increase from prioritized sectors suggests the prioritization of Nd, Dy, Co and Ga over B and Mn for improvements in EoL handling

1. Renewable energy, e-mobility, and ICT; 2. High = Global demand 2050 (low scenario) >100 % of current global supply; Low = Global demand 5050 < 10 % of current global supply
SOURCE: McKinsey, The net-zero materials transition: Implications for global supply chains (2023); S&P Global, Low prices for cobalt to persist in 2024 as demand slips (2023); EC, Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study (2023)

TO CAPTURE THE MOST VALUE FROM CRMS IN EEE AND BATTERIES, THREE COMPONENTS ARE MOST RELEVANT

Printed Circuit Boards

2022

0.8 wt.% of identified CRMs

20.0 % of identified CRMs value

2030

0.7 wt.% of identified CRMs

14.8 % of identified CRMs value −

NdFeB magnets

2022

1.8 wt.% of identified CRMs

35.0 % of identified CRMs value

2030

1.6 wt.% of identified CRMs

25.9 % of identified CRMs value −

Batteries

2022

97.3 wt.% of identified CRMs

44.8 % of identified CRMs value

2030

97.1 wt.% of identified CRMs

58.9 % of identified CRMs value +

Together, these three components represent 99.9 wt. % of the identified CRMs and 99.4 % of the primary material value in 2022

SOURCE: SCC analysis; Numbers are rounded to one decimal

MAGNETS AND PCBS FOLLOW A SIMILAR ROUTE IN THE EOL SYSTEM BUT WARRANT DIFFERENT INTERVENTIONS FOR THE CIRCULATION OF CRMS

The barriers highlight the need for interventions in collection, first treatment, and secondary processing

End of use

- Product hibernation
- Inaccurate disposal
- Illegal export

Collection

- Product breakage hinders reuse
- No sorting based on CRM value

First treatment

- Inadequate information and technology for CRM detection
- Difficult and time-consuming to separate magnets from products

Reuse

- Product obsolescence due to hibernation
- Uncertain functionality
- Limited reuse market

Secondary processing

- Lack of financial incentives for CRM recovery from the slag in the current metallurgical process, except for Pd which is extracted as a by-product at copper refineries

Sales of material

- Lack of established marketplace and demand for recycled material for many CRMs, especially REEs

Material recycling

- Mixing of materials and technical difficulties in separating complex components and alloys leads to the loss of magnets and their CRMs
- CRMs used only in niche PCBs are lost since their presence is largely unknown

NdFeB magnets | Printed Circuit Boards | Loss of component | Loss of material value

Illustration: Mapping of the EoL system, highlighting barriers for improved reuse or recycling of CRMs in Magnets and PCBs

Key intervention points

- For **magnets, detection** and **separation** are key enablers of recycling as the materials are currently lost in the mechanical recycling process
- For **PCBs**, the system mapping reveals potential for better recovery of CRMs from **secondary processing.** However, it is difficult to recycle CRMs other than Pd as they cannot be recovered through the current metallurgical process, or because targeting them may cause a decrease in processing efficiency for the primary material
- For both magnets and PCBs, **expansion of product reuse** is an opportunity for prolonging the useful life of the components and thereby the materials

SOURCE: Tillväxtanalys, Marknadsbarriärer för återvinning av metaller (2022); Expert interviews; SCC analysis

FOR BATTERIES, PRECISE SORTING AND DISCHARGING ARE NEEDED TO FACILITATE CLOSED-LOOP RECYCLING

The barriers highlight the need for interventions in collection and first treatment

End of use

- Product hibernation
- Inaccurate disposal
- Illegal export

Collection

- Mixing of batteries with different chemistries

First treatment and battery sorting

- Difficult and time-consuming to separate encapsulated batteries from products in regular EEE waste
- Manual handling lowers the precision when sorting batteries based on chemistry

Secondary use or processing

- Inadequate purity of processed materials for battery manufacturing

Sales of material

- Lack of established marketplace and demand for recycled material for many CRMs, especially REEs and graphite

Battery recycling

- Non-discharged batteries require pyrometallurgical treatment, which lowers the recovery rates of Li and Co while other CRMs are lost or downcycled
- Potential presence of hazardous materials

Batteries (alkaline, Li-ion, NiMH) Loss of component Loss of material value

Illustration: Mapping of the EoL system, highlighting barriers for improved reuse or recycling of CRMs

Key intervention points

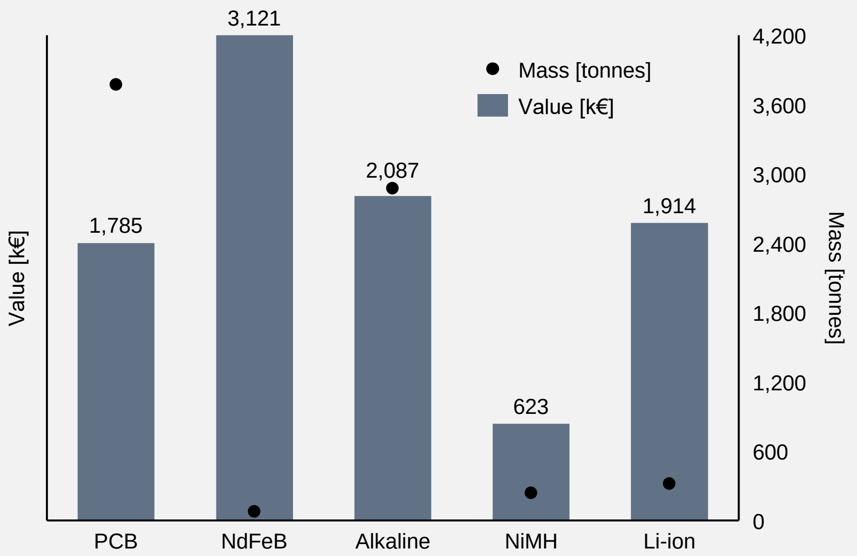
- Working to further improve **the collection rates** of batteries, especially for Li-ion, is crucial. This involves separating encapsulated batteries efficiently
- Precise **sorting** on chemistry and **discharging** are key enablers for improved recycling of CRMs, together with the removal of hazardous materials
- Enhancing the **quality of recycled materials** is essential for EoL battery waste to contribute to the EU's supply of CRMs, as only battery grade Mn, Li, and natural graphite are classified as strategic

SOURCE: Tillväxtanalys, Marknadsbarriärer för återvinning av metaller (2022); Expert interviews; SCC analysis

THE TOTAL MATERIAL VALUE INDICATES THE COST THRESHOLD FOR ACTIVITIES TO FACILITATE THE CIRCULATION OF CRMS

Printed Circuit Boards, NdFeB magnets, and batteries are key components to target for harvesting CRMs from the WEEE and waste batteries

Graph: Primary material value of all identified CRMs in 2025, per component



To build a viable business case, the material value must exceed the cost of EoL management and recycling to the required quality

The components hold a varying degree of primary CRM value:

- NdFeB magnets demonstrate the highest potential value of 41.6 k€ per tonne of component
- PCBs show the lowest potential value of 0.47 k€ per tonne of component
- The value of batteries is contingent on type but shows a higher value compared to mass than PCBs

The primary material value indicates the cost threshold for value-restoring EoL solutions for the highlighted components:

- Costs related to sorting, separation, transport, refinement, and potential handling of hazardous waste should all be covered by the material value
- In general, increased manual handling raises costs, underscoring the importance of identifying solutions for efficient sorting and separation

Disclaimer: The estimate relies on 2023-2024 primary material prices and does not include potential losses in material value or current revenues from end-of-life treatment

SOURCE: The Institute of Rare Earths and Metals, 2023; Daily Metal Price, 2023; Metal.com, 2023; MSE supplies, 2023

CONCLUSION AND RECOMMENDATIONS

A POTENTIAL BUSINESS CASE EXISTS FOR CRMS IN PCBS, MAGNETS, AND BATTERIES, WHILE OTHERS WILL REQUIRE FINANCIAL INCENTIVES

Conclusion

- The analysis suggests a **potentially viable business case** for value preservation or recycling of CRMs in NdFeB magnets, Printed Circuit Boards, and batteries, including alkaline, Li-ion, and NiMH
- Among these components, **magnets and batteries are the most relevant to proceed with** due to the existing design of the EoL system and their potential for closed-loop recycling. These components are expected to contain Mn, Co, Li, Nd, B, Dy, Pr, Ng, Ga, and Ce. However, all CRMs can probably not be recycled simultaneously due to the varying recycling technologies required
- Efforts to improve EoL management **should target collection and first treatment** which are the identified key intervention points:
    - NdFeB magnets should be detected and separated from the EoL product before the mechanical recycling process
    - Batteries need to be sorted with high precision according to chemistry to avoid material downcycling
- Addressing these intervention points will require **active collaboration between experts and actors across the material value chain,** including recyclers, sorting technology experts, and manufacturers of batteries and magnets

Recommended next steps

El-Kretsen is recommended to evaluate the feasibility of improving EoL management for magnets and batteries through two separate projects:

1. **Feasibility study for NdFeb magnets**

✓ Confirm which product groups to target for harvesting of magnets

✓ Identify solutions for detection and separation of magnets from WEEE

✓ Understand the business case for implementation

2. **Feasibility study for alkaline, Li-Ion and NiMh batteries**

✓ Identify solutions for sorting according to manufacturers' requirements

✓ Understand the business case for implementation

Additional recommendations

El-Kretsen is further recommended to:

- Advocate for policies to **incentivize improved EoL management** of CRMs currently lacking a positive business case
- Improve the **conditions for detection and separation** through collaboration with their member organizations, through initiatives such as product labelling for CRM content and product design for disassembly

SOURCE: SCC

RECOMMENDED NEXT STEPS INCLUDE THE EXECUTION OF TWO FEASIBILITY STUDIES FOR THE SELECTED COMPONENTS

Suggested collaboration with Stena Circular Consulting focuses on identifying solutions for the reuse and recycling of magnets and batteries

1. Feasibility study for NdFeb magnets

Activities

- Analysis and disassembly of selected products[1] to identify relevant product categories
- Research solutions for detection and separation of magnets to prepare for reuse or closed-loop recycling
- Evaluation of business case for implementation

Expected outcome

- ✓ Prioritization of product categories for reuse or closed-loop recycling of magnets
- ✓ Evaluation of theoretical feasibility, efficiency, and potential challenges associated with the identified solutions
- ✓ Insights into financial viability, benefits, and risk

2. Feasibility study for Alkaline, NiMH and Li-ion batteries

Activities

- Mapping of EoL metallurgical processes for portable batteries
- Research solutions for high-precision sorting and closed-loop recycling of portable batteries
- Evaluation of business case for implementation

Expected outcome

- ✓ Understanding of implications and limitations of existing EoL treatment processes for CRM recovery
- ✓ Evaluation of theoretical feasibility, efficiency, and potential challenges associated with the identified solutions
- ✓ Insights into financial viability, benefits, and risk

1.Likely to include one or a few of the following: cooling appliances, IT equipment (e.g., HDDs), high-end speakers and power tools

SOURCE: SCC

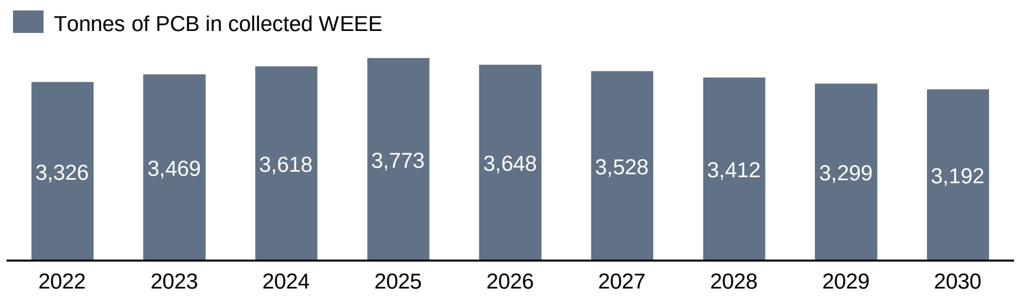
TOGETHER WE CREATE
A SUSTAINABLE TOMORROW

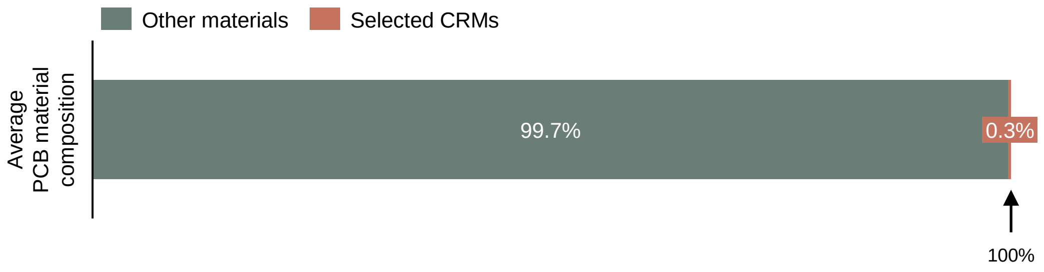
STENA
RECYCLING

APPENDIX A.
DETAILS PER COMPONENT

PRINTED CIRCUIT BOARDS (PCB)

The Waste from Electrical and Electronic Equipment consist of approximately 3 wt.% of PCBs

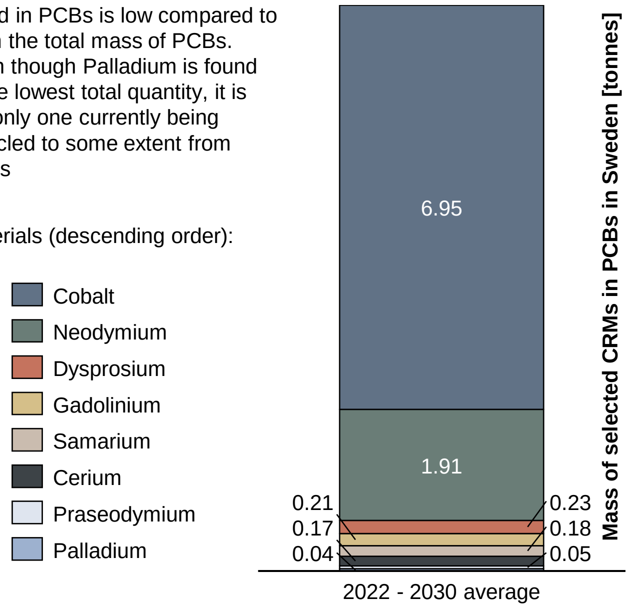




The selected CRMs are mainly found in the PCBs' surface-mounted components

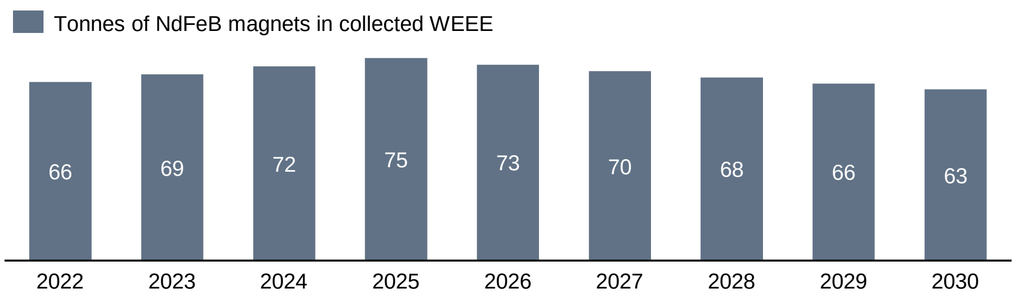
The total mass of most CRMs found in PCBs is low compared to even the total mass of PCBs. Even though Palladium is found in the lowest total quantity, it is the only one currently being recycled to some extent from PCBs

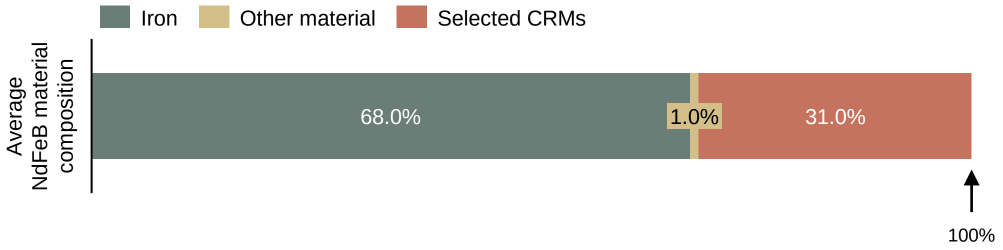
Materials (descending order):



NEODYMIUM-FERRITE-BORON (NDFEB) MAGNETS

The Waste of Electrical and Electronic Equipment consist of approximately 0.06 wt.% of magnets

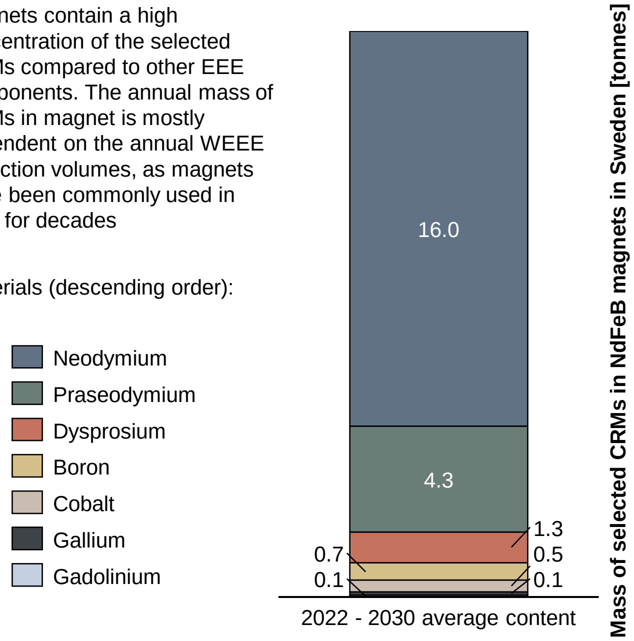




Neodymium and praseodymium are the most common CRMs

Magnets contain a high concentration of the selected CRMs compared to other EEE components. The annual mass of CRMs in magnet is mostly dependent on the annual WEEE collection volumes, as magnets have been commonly used in EEE for decades

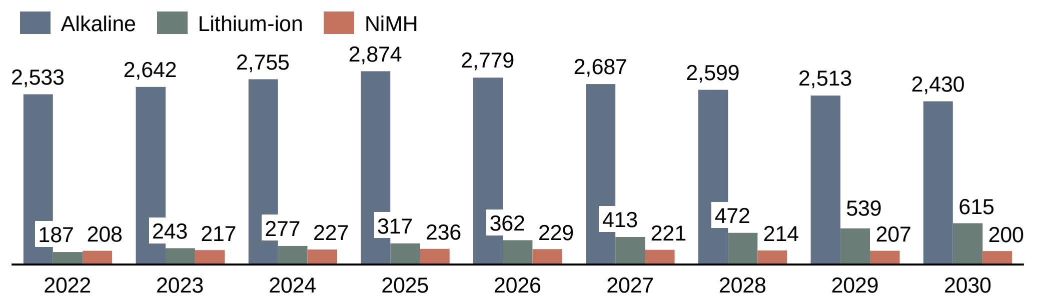
Materials (descending order):

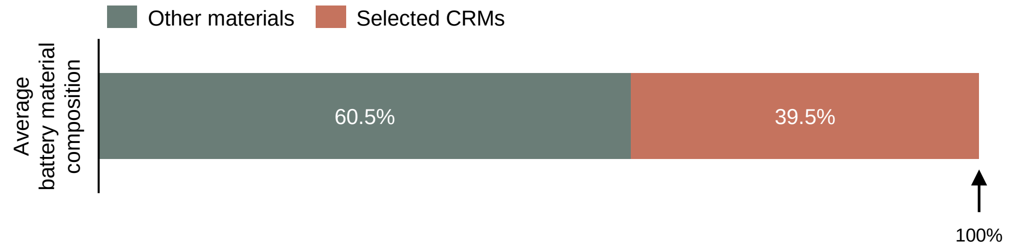


STENA RECYCLING

BATTERIES

Alkaline and NiMH collection rates have reached a steady state, while lithium-ion is growing

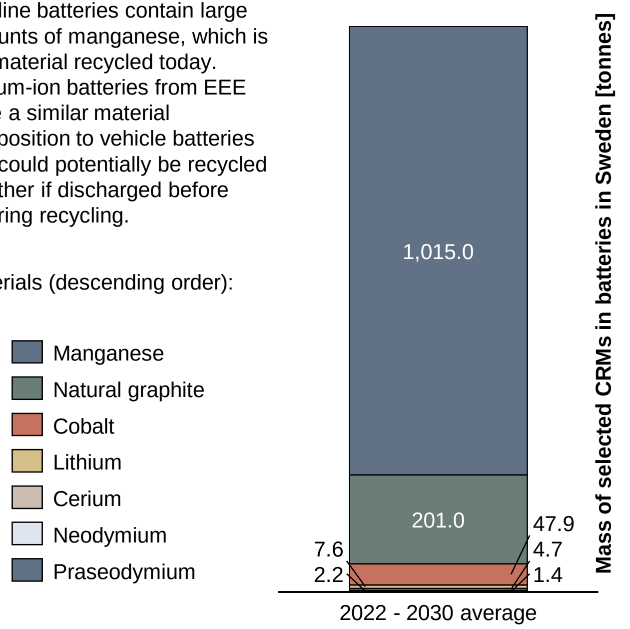




Alkaline batteries contain significant amounts of manganese

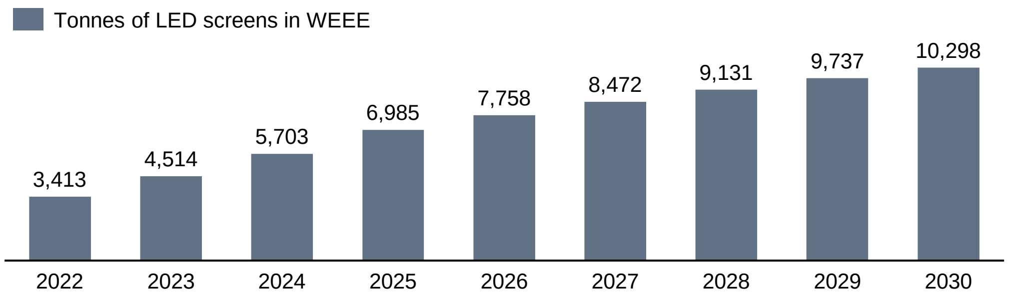
Alkaline batteries contain large amounts of manganese, which is not material recycled today. Lithium-ion batteries from EEE have a similar material composition to vehicle batteries and could potentially be recycled together if discharged before entering recycling.

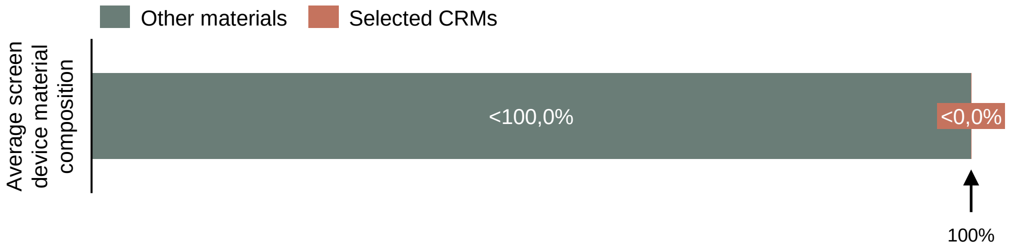
Materials (descending order):



LED SCREENS

LED as a consumer screen technology has become mainstream and will increase in WEEE over time



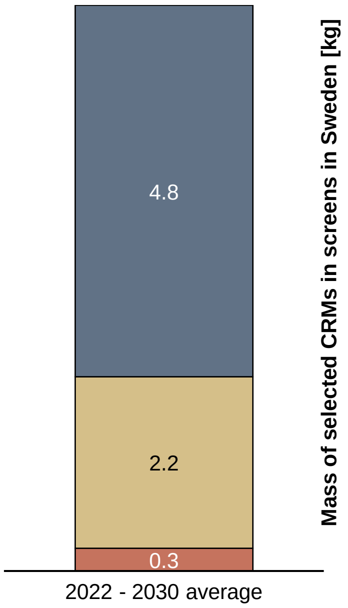


LED screens contain minuscule amounts of the selected CRMs

The selected CRMs are mainly used in LCD screens in the LED backlight in low concentrations. This means that even with an increasing collection of devices with LED screens, the total mass of CRMs will remain insignificant.

Materials (descending order):

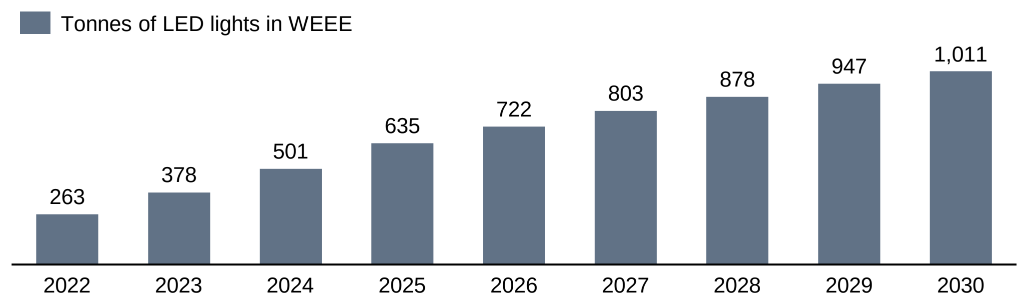
- Gallium
- Gadolinium
- Cerium

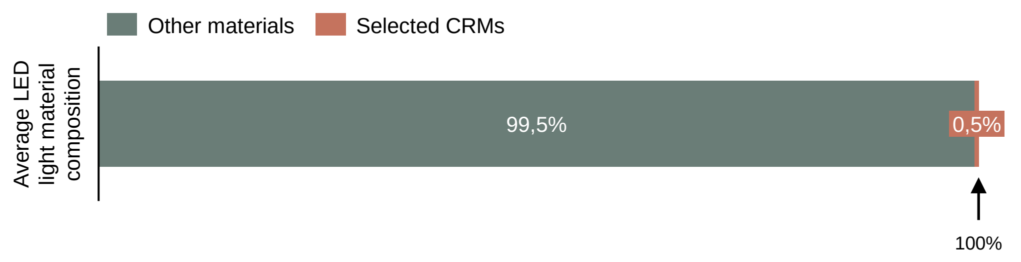


STENA RECYCLING

LED LIGHTS

LED occurrence in WEEE is increasing as older lighting technologies gets phased out

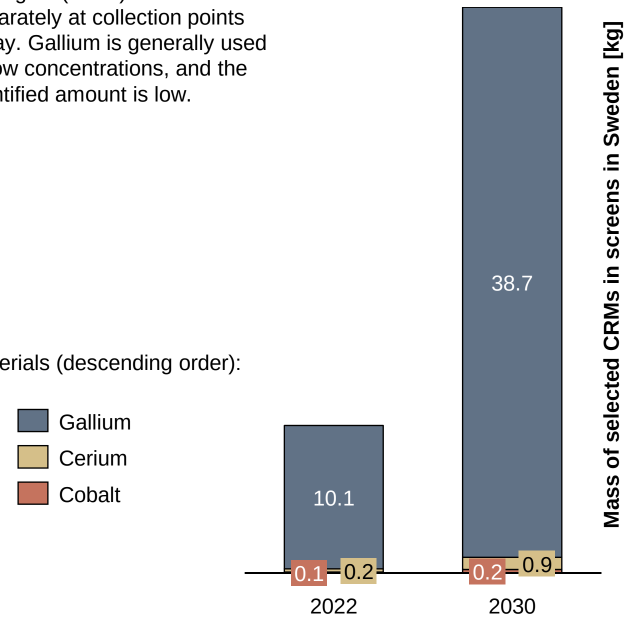




LED lights are a concentrated source of the selected CRMs

Led lights (bulbs) are collected separately at collection points today. Gallium is generally used in low concentrations, and the identified amount is low.

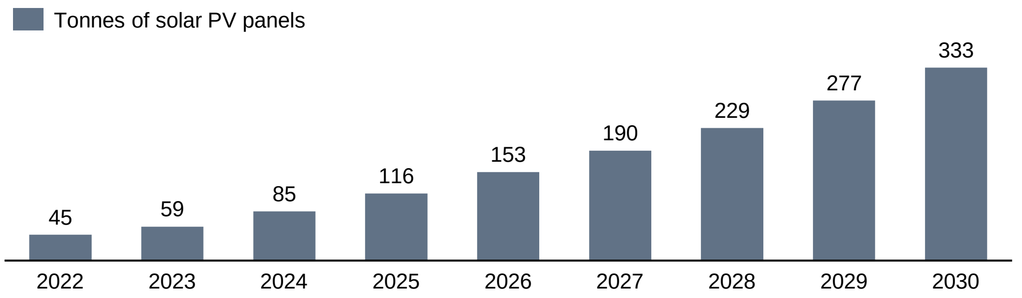
Materials (descending order):

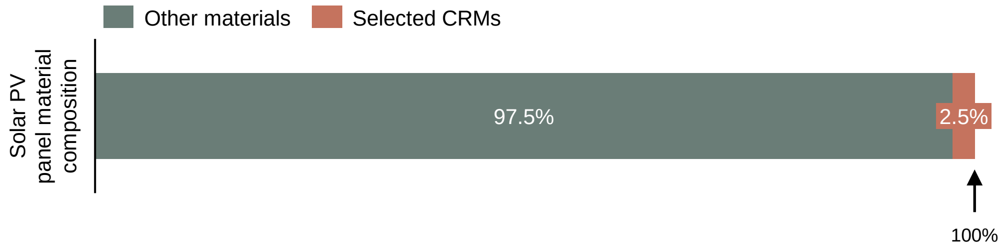


STENA RECYCLING

SOLAR PHOTOVOLTAIC PANELS

No significant mass of solar panels will reach their technical lifetime before 2030

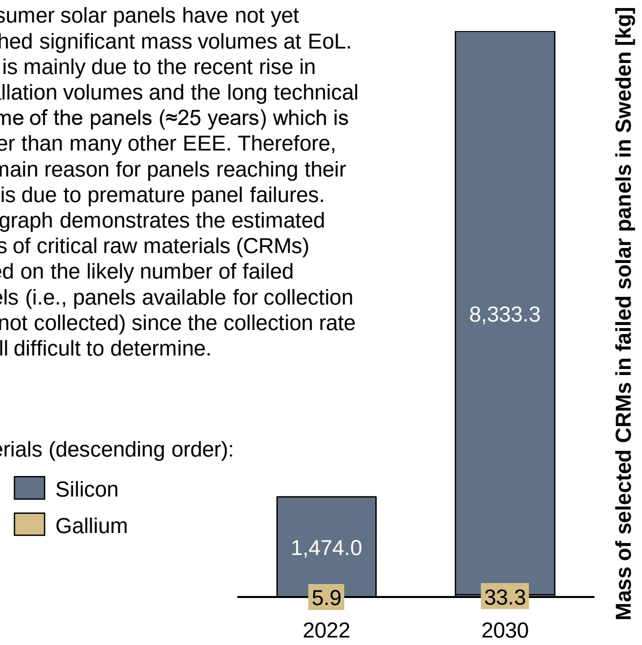




Solar panel collection will hopefully increase in the coming years

Consumer solar panels have not yet reached significant mass volumes at EoL. This is mainly due to the recent rise in installation volumes and the long technical lifetime of the panels (≈25 years) which is longer than many other EEE. Therefore, the main reason for panels reaching their EoL is due to premature panel failures. The graph demonstrates the estimated mass of critical raw materials (CRMs) based on the likely number of failed panels (i.e., panels available for collection and not collected) since the collection rate is still difficult to determine.

Materials (descending order):



STENA RECYCLING

APPENDIX B.
CRM ACT

THE CRM ACT IS LIKELY TO PUSH FOR INCREASED COLLECTION AND RECYCLING, WHILE INTRODUCING NEW REPORTING REQUIREMENTS

Status:

- The Parliament adopted the agreement on 12 December 2023, pending Council's endorsement

Objectives:

- To strengthen the EU's capacities along the different stages of the value chain and achieve self-sufficient and resilient CRM supply by 2030

Main proposed actions:

- Setting benchmarks by 2030 for domestic capacities
- Creating secure and resilient supply chains by streamlining permitting procedures
- Improving monitoring and risk mitigation capacities
- Diversifying the Union's imports of raw materials
- Improving sustainability and circularity of critical raw materials in the EU market by:
    - Setting up national programs to increase CRM waste collection, reuse, and recycling maturity
    - Establish reporting requirements of CRM quantities in recycled electronic waste to the Commission
    - Commission to detail high CRM content products and waste streams
  - Manufacturers must label products with permanent magnets indicating:
    - The presence of permanent magnets & and the type of permanent magnet material used
  - Producers must disclose the percentage of recycled materials in permanent magnets (above 0.2 kg) on a public website, including specific CRMs like neodymium and cobalt, within 3 years of regulation or 2 years after a delegated act
  - The Commission will enact a delegated act within 2 years to establish rules for calculating and verifying the recycled CRM content in permanent magnets
  - Post-2030, the Commission might set a minimum required percentage for recycled CRM content in permanent magnets

Future decision pending on:

- Whether goals will be set for each raw material individually or as an average across all 16 SRM
- Possible factors for goal setting could be based on weight, value-added, or other factors
- Adjustments to goals for each EU member state based on their reserves and mining capabilities

Potential implications for El-Kretsen:

- Prepare for increased collection targets, aligning with the EU's benchmarks for recycling critical raw materials
- Adapt to potential new reporting requirements to the Commission, detailing the quantities of critical raw materials recovered
- Stay informed on upcoming legislative procedures and how they will specifically impact the requirements and operations for WEEE collection and processing

SOURCE: COM/2023/160 final, Proposal Critical Raw Materials Act; SCC analysis

METHODOLOGY

METHODOLOGY DESCRIPTION FOR THE SELECTION OF COMPONENTS AND CRMS IN SCOPE OF THE PROJECT

Selection of components

Step 1: Identification of the most relevant components in EEE and batteries

The initial selection of six components was made through a literature review, examining academic literature, white papers, and official publications focusing on the mass and value of Critical Raw Materials (CRMs) in Electrical and Electronic Equipment (EEE) and batteries.

Step 2: Definition of the type of component

Market data and waste collection statistics were used to further define the type of component. The scope was limited to the following:

- Permanent magnets. Includes NdFeB magnets, as it is the main type of permanent magnet used in EEE.
- Photovoltaic panels. Includes crystalline-silicon panels (c-Si) which represented 95 % of the global production of PV panels in 2021. Thin-film solar PV panels were excluded from the scope of the project.
- Batteries. Includes alkaline (non-rechargeable), Li-ion and NiMH batteries (rechargeable). Selected as they represent the largest share of battery types in the small portable battery waste stream.
- Technology for lights and display. Limited to LED technology as it is the dominating technology for lighting and display. OLED and fluorescent lighting technology were excluded. OLED still represent a relatively niche technology, while sales of fluorescent lighting technology are prohibited in the EU market.
- Printed Circuit Board. No limitations in scope.

Selection of critical raw materials

Step 1: Selection of critical raw materials classified as strategic

The scope was limited to the critical raw materials that are classified as strategic by the CRM Act, as these are expected to be most impacted by upcoming legislation.

Step 2: Use of exclusion criteria to further narrow down the scope

The scope of critical and strategic raw materials was further limited using the following exclusion criteria:

1) Not found within electronics/batteries
2) Only used for niche applications
3) No available data on concentration
4) Primarily used as alloying material

The following strategic and critical raw materials were excluded from the scope during the project:

- Bismuth (1)
- Titanium metal (2)
- Platinum (2/3)
- Tungsten (2/3)
- Germanium (3)
- Terbium (3)
- Ruthenium (2/3)
- Rhodium (2/3)
- Iridium (2/3)
- Magnesium (4)

OVERVIEW OF REFERENCES FOR THE ESTIMATION OF CRM CONTENT IN COMPONENTS (1/3)

Estimation of CRM content

The CRM content of each product group was estimated using data from published research

Component	Limitations of data	References
▪ LED light	▪ Difficult to estimate LED content in all LED-containing fractions, therefore only pure LED sources are examined	Cenci et al., Precious and critical metals from wasted LED lamps: characterization and evaluation, 2022; Olivieira et al., A review of the current progress in recycling technologies for gallium and rare earth elements from light-emitting diodes, 2021
▪ LED display	▪ Categories that contain LED displays are combined with other types of displays, making estimations more difficult. The concentration of CRMs is also varying; however, the quantities are overall small	Yeom et al., Environmental Effects of the Technology Transition from Liquid-Crystal Display (LCD) to Organic Light-Emitting Diode (OLED) Display from an E-Waste Management Perspective, 2018; Rochetti et al., Cross-current leaching of indium from end-of-life LCD panels, 2015; Buchert et al., Recycling critical raw materials from waste electronic equipment, 2012

OVERVIEW OF REFERENCES FOR THE ESTIMATION OF CRM CONTENT IN COMPONENTS (2/3)

Estimation of CRM content

The CRM content of each product group was estimated using data from published research

Component	Limitations of data	References
▪ NdFeB magnet	▪ NdFeB content varies between samples and WEEE categories, Terbium was rare and found in few examples of WEEE	Lixandru et al., Identification and recovery of rare-earth permanent magnets from waste electrical and electronic equipment, 2017; Tanvar et al., Characterization and evaluation of discarded hard disc drives for recovery of copper and rare earth values, 2019; Smodis et al., The Content Of Rare-earth Elements In Mobile-phone Components, 2018; Stein et al., Recovery of Rare Earth Elements Present in Mobile Phone Magnets with the Use of Organic Acids, 2022; Heim et al., NdFeB Permanent Magnet Uses, Projected Growth Rates and Nd Plus Dy Demands across End-Use Sectors through 2050: A Review, 2023
▪ Solar PV	▪ Most panels installed before 2020 contain B instead of Ga but since the installed base of B will not increase further, only Ga is considered ▪ Calculations only consider the solar panels, no other equipment related to a solar energy system	Guzik et al., The EU's demand for selected critical raw materials used in the photovoltaic industry, 2022; Wang et al., A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology, 2022; Carrara et al., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, 2023

OVERVIEW OF REFERENCES FOR THE ESTIMATION OF CRM CONTENT IN COMPONENTS (3/3)

Estimation of CRM content

The CRM content of each product group was estimated using data from published research

Component	Limitations of data	References
▪ Printed circuit board	▪ Contains most CRMs, however, some specific material amount is lacking and is potentially only used in certain high-end products	Bourgeois et al., A simple process for the recovery of palladium from wastes of printed circuit boards, 2020; Efstratiadis and Michailidis, Sustainable Recovery, Recycle of Critical Metals and Rare Earth Elements from Waste Electric and Electronic Equipment (Circuits, Solar, Wind) and Their Reusability in Additive Manufacturing Applications: A Review, 2022; De Oliveira et al., Study of Metal Recovery from Printed Circuit Boards by Physical-Mechanical Treatment Processes, 2021; Charles et al., 2020; Vermesan et al., Advanced Recovery Techniques for Waste Materials from IT and Telecommunication Equipment Printed Circuit Boards, 2019; Manoochehri et al., A contribution to future Critical Raw Materials Recycling, 2020; Huang et al., Assessment of precious metals positioning in waste printed circuit boards and the economic benefits of recycling, 2022; Kaya, Electronic Waste and Printed Circuit Board Recycling Technologies, 2019; Duan et al., Examining the technology acceptance for dismantling of waste printed circuit boards in light of recycling and environmental concerns, 2011
▪ Batteries	▪ Different chemistries for Li-ion batteries imply a varying material content where Co content varies the most	Stena Recycling, 2024; El-Kretsen, 2024; Dushyantha et al., The Role of Permanent Magnets, Lighting Phosphors, and Nickel-Metal Hydride (NiMH) Batteries as a Future Source of Rare Earth Elements (REEs): Urban Mining Through Circular Economy, 2023; Constantine et al., Recovery of rare earth elements from spent NiMH batteries using subcritical water extraction with citric acid, 2022

ASSUMPTIONS AND LIMITATIONS FOR ESTIMATES OF CRM MASS IN SELECTED COMPONENTS (1/2)

Estimation and forecast of CRM mass

Component	Assumptions	Limitations	References
▪ WEEE	▪ Growth based on forecasted WEEE per capita collection	▪ Does not account for changes between WEEE categories	▪ SCB, 2023 ▪ Pirvu et al., E-waste and responsible consumption in EU countries – developments and forecasts 2025-2030, 2023
▪ Printed circuit board	▪ WEEE consist of 3 wt.% PCB ▪ Concentration is stable	▪ Estimated amount is strongly connected to the annual WEEE ▪ Magnet materials face risk of double counting	▪ Kaya, Electronic Waste and Printed Circuit Board Recycling Technologies, 2019 ▪ Expert interview
▪ NdFeB magnet	▪ Consumption based on Sweden's share of global GDP (PPP) ▪ Concentration in WEEE is stable	▪ Estimated amount is strongly connected to the annual WEEE	▪ IMF, 2024 ▪ Heim II, NdFeB Permanent Magnet Uses, Projected Growth Rates and Nd Plus Dy Demands across End-Use Sectors through 2050: A Review, 2023
▪ Batteries (Alkaline, NiMH)	▪ Alkaline and NiMH sales and collection are stable, linear forecast	▪ -	▪ El-Kretsen data ▪ SCB, 2023
▪ Batteries (Li-ion)	▪ Li-ion sales are increasing linearly, and collection increasing exponentially	▪ Few data points, leading to more uncertain forecast	▪ El-Kretsen data ▪ SCB, 2023

ASSUMPTIONS AND LIMITATIONS FOR ESTIMATES OF CRM MASS IN SELECTED COMPONENTS (2/2)

Estimation and forecast of CRM mass

Component	Assumptions	Limitations	References
▪ LED lights	▪ Linear growth until 2030 to 50% share of bulbs	▪ Little historic data points of LED lights share of light bulbs	▪ El-Kretsen data
▪ LED screens (TVs, monitors, notebooks, laptops)	▪ Per unit material data ▪ Estimated average product weight ▪ LED TVs: Linear growth to 100 % share of TVs in 2030 ▪ Monitors: Linear growth to 50 % share of WEEE category 3.3 in 2030 ▪ Notebook: Linear growth to 10 % share of WEEE category 3.3 in 2030 ▪ Laptops: 0.6 % share off WEEE	▪ Limited data availability	▪ El-Kretsen data
▪ Solar PV	▪ Installed solar capacity based on Energimyndigheten forecast ▪ Power per module is 0.3 kW	▪ Collection rate is difficult to determine	▪ Energimyndigheten, 2023 ▪ SCB, 2023