



Nordic Council
of Ministers

Evaluation of potential measures to reach the recycling benchmarks of the Critical Raw Materials Act



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Summary

Critical raw materials (CRMs) are defined by the EU as materials that combine high economic importance with significant supply risk. CRM supply risks are amplified by increasing CRM consumption rates driven by growing populations, expanding economies, and the transition to green and digital technologies that require significantly more CRMs than the platforms they replace. Additionally, declining grades in mineral ores from which primary CRMs are extracted result in higher production costs and greater environmental footprints, further reducing the social acceptance of mining in many areas where CRM extraction occurs. Increasing supply risks are also caused by rising geopolitical tensions worldwide, which has led to growing protectionism and CRM-trade restrictions and disruption of distribution routes.

To mitigate future supply risks for CRMs that are comparable in importance for economic growth and human welfare as energy, the EU has launched the Critical Raw Materials Act (CRMA), which provides regulations to strengthen European extraction and refinery capacity. This strategy includes increased recycling operations and creating a market for secondary CRM materials.

This report is the second of three reports that consider how to ensure better resource efficiency regarding CRMs in the Nordics. While the first report presented an overview of potential recycling options for CRMs in the Nordic region,^[1] this report presents an extended list of more direct measures and instruments that may increase Nordic CRM recycling. A selection of these measures is given a more in-depth evaluation.

Since the first report was published in February 2024, CRMA has entered into force, which means that Denmark, Finland and Sweden are already bound by the regulation, while Norway, Iceland and Liechtenstein are currently assessing its EEA relevance.

Article 26 of the CRMA mandates national programs to increase waste collection with high CRM recovery potential and ensure their introduction into the appropriate recycling systems. The measures outlined in this report represent suggestions to be considered when setting up these programs.

General considerations regarding CRM-recycling

CRMs incorporated into products and materials are continuously lost through all stages of product life. Losses occur for various reasons: some CRMs are lost due to suboptimal collection when CRM-containing products and materials are discarded as waste, while others are lost because of inadequate sorting and pre-treatment before recycling. Additional losses result from thermodynamic and technical limitations of the recycling process used for CRM recovery. Moreover, some secondary CRM materials from a recycling process may be rejected as new raw materials due to quality concerns, further reducing the end-of-life recycling input rate.

Along with reduced supply risks, increased CRM-recycling also comes with additional environmental benefits. CRM-recycling operations are associated with a negative environmental footprint due to necessary inputs of energy and chemicals and associated emissions and waste products. However, this footprint is usually only a fraction of the footprint of the primary CRMs

1. <https://pub.norden.org/temanord2024-513/temanord2024-513.pdf>

that the recycling operation replaces. For instance, secondary aluminium production only requires a tenth of the energy input necessary for producing an equivalent amount of primary aluminium. Also, it eliminates the generation of large amounts of mineral waste during the mining and processing of bauxite.

Status for European CRM-recycling

CRMA introduces a recycling benchmark for strategic raw materials of 25% within 2030. An analysis of European recycling rates for different CRMs identifies three different segments based on how mature respective recycling operations currently are. For some CRMs like tungsten (W), copper (Cu), antimony (Sb) and PGMs, recycling already exceeds the CRMA benchmark of 25%. For approximately nine other CRMs, the secondary value chains are sufficiently mature to make the 25% recycling benchmark appear achievable with limited efforts. The most critical strategic steps towards achieving the 25% recycling goal include measures to support and further develop these secondary value chains, together with measures to improve the collection and sorting of waste streams that are currently utilised or could potentially be used as feedstock for these recycling operations. It may be argued that while 25% is a politically defined benchmark for each CRM, it makes sense to aim for significantly higher recycling rates for some CRMs from an industrial and environmental perspective.

Global and European recycling is only marginal for some CRMs like boron (B), fluorspar (CaF_2), helium (He), vanadium (V), graphite (C) and REE if it exists at all. Piloting and demonstrating available recycling technologies are therefore considered the most critical measures necessary for moving these secondary value chains towards the CRMA recycling benchmark.

So far, no real Nordic or European recycling yet exists for post-consumer CRMs like bismuth (Bi), beryllium (Be), gallium (Ga), niobium (Nb) and silicon metal (Si). For some of these CRMs, there are neither mature nor proposed recycling technologies available for any start-up projects. Developing recycling technologies that allow secondary value chains for this CRM-group to be established will require significant R&D efforts. However, current market conditions for these CRMs make it unlikely to achieve without large-scale economic support schemes.

General considerations when setting up a national program for increased CRM-recycling

When designing strategies for increased Nordic CRM-recycling, it's crucial to consider the following factors:

1. **Regulatory Alignment:** Measures should be in line with both current and anticipated national and European regulations. Relevant EU regulations include:
 - Waste Framework Directive
 - Extractive Waste Directive
 - WEEE Directive
 - Battery Directive
 - End of Life Vehicle Regulation
 - Eco Design Directive

2. **Available Resources:** Consider the available waste streams that can serve as raw material for recycling operations, as well as the existing technologies, expertise, and industrial infrastructure in the region. The following waste streams should be evaluated for Nordic CRM-recycling:
 - Mineral tailings
 - Jarosite waste from the zinc industry
 - Electric Arc Furnace (EAF) dust and slag from the steel industry
 - Spent pot liner and dross, slag, and dust from primary aluminium production
 - WEEE
 - Scrapped vehicles
 - Shredder residues
 - Ash from waste incineration
3. **Existing Industrial Value Chains:** Current industrial value chains can lead or support new CRM-recycling projects. The Nordic base metals industries fleet serves as a significant platform for rapid CRM-recycling development.
4. **Established Companies vs. Start-ups:** Established companies often have the advantage over start-ups when it comes to branching out. They can leverage in-house expertise for project planning and design, secure investment capital more readily, and obtain necessary governmental permits and off-take agreements for their secondary CRM product with less risk.
5. **Potential of CRM-containing Waste as Feedstock:** CRM-containing waste can sometimes be used as additional feedstock in primary production processes. However, contamination issues and technical considerations may limit these options or require pretreatment steps. Relevant Nordic industries to consider include aluminium, zinc, copper, nickel, silicon, manganese, and graphite production. Although not a CRM, the steel industry should also be considered due to its significant consumption and recycling of CRMs as alloy components.

Taking these factors into account, a more robust and efficient Nordic CRM-recycling strategy can be developed.

Instruments and measures for better CRM-recycling in the Nordics

A list was set up consisting of 85 potential measures expected to increase Nordic CRM-recycling significantly. The list was based on a set of selection criteria, including high effectiveness and cost efficiency, relevance for Nordic market conditions, and the broadest possible scope regarding affected value chains and the number of CRMs. Based on this list (see Appendix 2), sixteen measures were selected for an extended evaluation presented in Chapter 4 of this report. Measures that are given an extended evaluation are grouped into three categories and include:

- A. **Mapping CRM- waste streams**
 - A1 National program for mapping CRM- levels in relevant waste streams.
- B. **Collection and pre-processing**
 - B1 R&D program for the development of better sorting technology.
 - B2 Picking and sorting of components from circuit boards before recycling
 - B3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding
 - B4 Disassembly of EEE components in discarded vehicles before shredding
 - B5 Organized emptying and dismantling of hand-held fire extinguishers
 - B6 Assess the possibility of incineration of selected waste streams in selected waste incineration plants to increase the concentration of CRM- levels in the ash residues
 - B7 Analyse wastewater from geothermal power stations for anhydrous CRMs
- C. **Better recycling solutions**
 - C1 R&D program for the development of new or more efficient CRM recycling processes.
 - C2 Develop business models that enable the establishment of networks of Nordic steel plants that more clearly specialize in the recycling of specific alloy qualities
 - C3 Develop business models that enable the establishment of networks of Nordic secondary aluminium plants specializing in the recycling of specific alloy grades
 - C4 Establishment of a Nordic recycling plant for gallium from industrial wastes from zinc and aluminium
 - C5 Development of recycling process for circuit boards and other EEE waste that recovers more CRMs
 - C6 Develop business models that enable the restart of closed CRM-recycling facilities
 - C7 Development of technology for the extraction of CRMs from ash residues

Sammendrag (norsk)

Kritiske råmaterialer (CRM) defineres av EU som råmaterialer som både har høy økonomisk nytteverdi og samtidig er forbundet med en betydelig forsyningsrisiko. At denne forsyningsrisikoen øker skyldes blant annet økende CRM-forbruk som følge av voksende befolkningspopulasjoner og økonomier, samt grønt skifte og digitale omstillinger som i mange tilfeller krever langt større mengder CRM enn teknologiplattformene som erstattes.

Samtidig reduseres gehalter i gjenværende mineralmalmer som primære CRM-er utvinnes fra, noe som fører til at fremtidig CRM-produksjon blir forbundet med større produksjonskostnader og miljømessige fotavtrykk enn tidligere utvinning. Disse forholdene bidrar også til den fallende sosiale aksepten for mineralutvinning som vi ser i mange områder hvor CRM-utvinning finner sted. Økende forsyningsrisiko er også et resultat av økende geopolitiske spenninger som har ført til økende proteksjonisme og restriksjoner på handel og distribusjon av CRM-er.

For å redusere fremtidig CRM-forsyningsrisiko har EU lansert Critical Raw Materials Act (CRMA) som blant annet inneholder bestemmelser for å styrke europeisk utvinnings- og raffineringkapasitet for kritiske råmaterialer. Økt gjenvinning og etablering av et marked for sekundære CRM-er er også en viktig del av denne strategien. Denne rapporten er den andre av tre rapporter som drøfter hvordan Norden kan bidra til mer effektiv CRM-ressursutnyttelse. Mens den første rapporten presenterte en oversikt over utfordringer og mulighetsrom for Norden når det gjelder økt CRM-gjenvinning, inneholder denne rapporten en utvidet liste over mulige tiltak og virkemidler som kan øke nordisk CRM-resirkulering og gir en utfyllende beskrivelse av seksten utvalgte tiltak for dette. Siden den første rapporten ble publisert i februar 2024 har CRMA tredd i kraft, noe som betyr at Danmark, Finland og Sverige allerede er bundet av forordningen mens Norge og Island vurderer hvorvidt forordningen skal betraktes som EØS-relevant.

Artikkel 25 i CRMA krever at medlemsstater utarbeider nasjonale programmer som beskriver hvordan statene planlegger å øke innsamlingen av avfall med CRM-gjenvinningspotensial og sikre at disse avfallsstrømmene ledes til velfungerende gjenvinningssystemer. Tiltakene som er omtalt i denne rapporten representerer forslag som kan vurderes ved utforming av dette programmet.

Generelle betraktninger angående CRM-gjenvinning

CRM-er som inngår i produkter og materialer går løpende tapt gjennom alle stadier av produktenes levetid. Noe CRM går tapt på grunn av mangelfull innsamling av CRM-holdige avfallsstrømmer. Noe CRM går tapt på grunn av utilstrekkelig sortering og forbehandling før resirkulering, og noe CRM-tap er et resultat av termodynamiske og tekniske begrensninger i prosessene som brukes til å CRM-gjenvinning. Fordi dagens gjenvinningsordninger i noen tilfeller leverer produkter som har utfordringer når det gjelder å oppfylle kvalitetskrav som tilsvarende primære materialer må innfri vil også noe sekundært CRM ikke aksepteres av markedet, noe som reduserer resirkuleringsraten ytterligere.

I tillegg til å redusere forsyningsrisiko, gir økt CRM-gjenvinning også i mange tilfeller betydelige miljøfordeler. Sammenlignet med primære CRM-er som sekundære CRM-er erstatter vil det samlede miljøfotavtrykket i form av energiforbruk, arealbeslag, generte avfallsmengder og spredning av forurensning fra produksjonen normalt være betydelig lavere

Eksempelvis krever produksjon av sekundær aluminium bare en tiendedel av energien som er nødvendig for produksjon av en tilsvarende mengde primæraluminium, og unngår også at det genereres store mengder mineralavfall under gruvedrift og prosessering av bauxitt.

Status for europeisk CRM-resirkulering

CRMA introduserer et mål om at CRM-gjenvinning skal kunne dekke minimum 25 % av EUs eget konsum innen 2030.^[2] En gjennomgang av europeiske gjenvinningsrater for ulike CRM-er identifiserer tre ulike segmenter basert på hvor modne verdikjedene er per i dag. For noen CRM-er som wolfram, kobber, antimon og platinagruppermetaller oppfylles gjenvinningsmålet på 25 % allerede. For ni andre CRM-er er de sekundære verdikjedene tilstrekkelig modne til at 25 %-målet synes oppnåelig med begrenset innsats. Tiltak for å støtte og videreutvikle disse sekundære verdikjedene sammen med tiltak for å forbedre innsamling og sortering av avfallsstrømmer som i dag brukes eller kan brukes som råstoff for disse gjenvinningsprosessene anses for å være de viktigste hovedtiltakene for å bevege seg mot 25 % målet. Ut fra et industri- og miljøperspektiv vil det for mange CRM-er være fornuftig å sikte mot enda høyere gjenvinning enn 25 %.

For noen CRM-er som eksempelvis bor, flusspat, helium, vanadium, grafitt og REE er både europeisk og global gjenvinning mer marginal. Pilotering og demonstrasjon av tilgjengelige resirkuleringsteknologier anses derfor som viktigste tiltak for å bygge ut behandlingskapasiteten til disse sekundære verdikjedene.

Så langt finnes det ingen reell nordisk eller europeisk gjenvinning av avfall etter forbruk for beryllium, gallium, niob silisiummetall eller vismut. For noen av disse CRM-ene finnes det heller ikke tilgjengelige teknologier for muliggjør umiddelbar etablering av gjenvinningsoperasjoner. For å utvikle gjenvinningsteknologier som muliggjør etablering av sekundære verdikjeder for disse CRM-ene, vil det være nødvendig med massiv FoU-innsats. Ut fra dagens markedsituasjon for disse CRM-ene synes det usannsynlig at dette kan oppnås uten store økonomiske støtteordninger.

Generelle hensyn ved etablering av et nasjonalt program for økt CRM-resirkulering

Ved utforming av strategier for økt nordisk CRM-resirkulering, er det vesentlig å ta hensyn til følgende faktorer:

1. **Regelverkstilpasning:** Tiltak bør være i overensstemmelse med både gjeldende og forventet nasjonal og europeisk lovgivning. Relevante EU direktiver og forordninger inkluderer:
 - Rammedirektivet for avfall
 - Mineralavfallsdirektivet
 - WEEE-direktivet
 - Batteriforordningen
 - Kjøretøysforordningen
 - Økodesigndirektivet

2. Målet gjelder kun strategiske råmaterialer som i øyeblikket omfatter 27 av totalt 51 individuelle CRM.

2. **Tilgjengelige ressurser:** Tiltak bør ta utgangspunkt i tilgjengelige avfallsstrømmer som kan tjene som råstoff for gjenvinningsoperasjoner, så vel som tilgjengelige teknologier, ekspertise og industriell infrastruktur i regionen. Følgende avfallsstrømmer bør vurderes for nordisk CRM-resirkulering:
 - Mineralavfall
 - Jarositt-avfall fra sinkindustrien
 - EAF-støv og slagg fra stålindustrien
 - Kassert ovnsforing samt dross, slagg og støv fra primær aluminiumsproduksjon
 - EE-avfall
 - Utrangerte kjøretøy
 - Restavfall fra kverning av metallskrap og EE-avfall
 - Aske fra avfallsforbrenning
3. **Eksisterende industrielle verdikjeder:** Nåværende industrielle verdikjeder kan lede eller støtte nye CRM-gjenvinningsprosjekter. Den nordiske metallindustrien kan fungere som en viktig plattform for rask oppbygging av sekundær CRM-produksjon.
4. **Etablerte selskaper vs. oppstartsbedrifter:** Det er ofte lettere for eksisterende selskaper å forgrene seg enn det er for oppstartsbedrifter å lykkes. Etablerte virksomheter kan ofte utnytte intern ekspertise for prosjektplanlegging og prosessdesign, sikre lettere tilgang til investeringskapital, innhente nødvendige driftstillatelser og konsesjoner, samt inngå salgssavtaler for deres sekundære CRM-produkt med mindre risiko.
5. **Potensial for CRM-holdig avfall som råstoff:** CRM-holdig avfall kan noen ganger brukes som ekstra råstoff i primærproduksjonsprosesser. Forurensningsutfordringer og tekniske hensyn kan imidlertid begrense denne praksisen eller kreve at avfallsråstoffet gjennomgår en viss forbehandling. Relevante nordiske industrier å vurdere som mulige aktører eller støttespillere for utbygging av sekundær CRM-produksjon inkluderer produsenter av aluminium, sink, kobber, nikkel, silisium, mangan og grafitt. Selv om stål ikke er en CRM, bør også stålindustrien vurderes på grunn av den betydelige CRM-mengden som inngår som legeringskomponenter.

Ved å vurdere disse faktorene kan en mer robust og effektiv nordisk CRM-resirkuleringsstrategi utvikles.

Tiltak for bedre CRM-resirkulering i Norden

En liste bestående av 85 potensielle tiltak som forventes å kunne øke nordisk CRM-resirkulering ble satt opp. Listen var basert på et sett med kriterier som inkluderte høy effektivitet og kostnadseffektivitet, relevans for nordiske markedsforhold og et bredest mulig omfang når det gjelder berørte verdikjeder og antall CRM-er. Basert på denne listen (se vedlegg 2) ble seksten tiltak valgt ut for en utvidet evaluering som presenteres i kapittel 4 i denne rapporten. Tiltak som gis en utvidet evaluering er gruppert i tre kategorier og inkluderer:

A. **Kartlegging av CRM-avfallsstrømmer**

A1 Nasjonalt program for kartlegging av CRM-nivåer i relevante avfallsstrømmer.

B. **Innsamling og forbehandling**

B1 FoU-program for utvikling av bedre sorteringsteknologi.

B2 Plukking og sortering av komponenter fra kretskort før gjenvinning

B3 Mer manuell demontering og oppskjæring av skrapmetall og kasserte kjøretøy før kverning

B4 Bedre demontering av EE-komponenter i kasserte kjøretøy før kverning

B5 Organisert tømning og demontering av håndholdte håndslukningsapparater

B6 Vurdere mulighet for forbrenning av utvalgte avfallsstrømmer i dedikerte avfallsforbrenningsanlegg for å oppkonsentrere CRM-nivåer i askerestene

B7 Analysere avløpsvann fra geotermiske kraftverk for vannløste CRM-er

C. **Bedre resirkuleringsløsninger**

C1 FoU-program for utvikling av nye eller mer effektive CRM-gjenvinningsprosesser.

C2 Utvikle forretningsmodeller som muliggjør etablering av nettverk av nordiske stålverk som tydeligere spesialiserer seg på resirkulering av spesifikke legeringskvaliteter

C3 Utvikle forretningsmodeller som muliggjør etablering av nettverk av nordiske sekundære aluminiumverk som spesialiserer seg på resirkulering av spesifikke legeringskvaliteter

C4 Etablering av nordisk gjenvinningsanlegg for gallium fra industriavfall fra sink og aluminium

C5 Utvikling av gjenvinningsprosess for kretskort og annet EE-avfall som gjenvinner flere CRM-er

C6 Utvikle forretningsmodeller som muliggjør gjenoppstart av nedstengte CRM-gjenvinningsanlegg

C7 Utvikling av teknologi for utvinning av CRM fra askerester

C8 Rasjonalisere bruk av metall legeringer som forenkler CRM-gjenvinning

1. Introduction

Raw materials are defined by the EU as substances in the processed or unprocessed state used as input for the manufacturing of intermediate or final products. Substances predominantly used as food, feed or combustion fuel are, however, excluded from this definition and not considered as raw materials.^[3]

Critical raw materials (CRM) are raw materials defined by the EU as having a combination of high economic importance and significant supply risk. To mitigate future supply risks for CRMs, the EU has launched the Critical Raw Materials Act, which provides regulations to strengthen European extraction and refinery capacity. This strategy also includes increased recycling operations and the creation of a market for secondary CRM materials.

This report is the second of three reports considering how to ensure better resource efficiency regarding critical raw materials (CRM) in the Nordics. Whereas the first report presented an overview of potential recycling options for CRMs in the Nordics, this report contains an extended list of possible measures and instruments that may increase CRM-recycling in the Nordics and takes a more in-depth view of a selected number of these.

Since the first report was published in February 2024, the Critical Raw Material Act of the EU has entered into force, which means that the regulation already bound Denmark, Finland and Sweden, while Norway, Iceland and Liechtenstein are currently assessing its EEA relevance.

Article 26 of the Critical Raw Materials Act (CRMA) requires states bound by the regulation to adopt and implement a national programme containing measures designed to increase waste collection with high CRM recovery potential and ensure their introduction into the appropriate recycling system. The goal is to maximise the availability and quality of recyclable material for critical raw material recycling facilities. This report suggests possible measures and instruments to consider when designing these programmes.

It should also be mentioned that since the first report was published, the United Nations has opened a panel on critical raw materials, highlighting that CRM-supply risk is a global concern,^[4] not only limited to Europe. Furthermore, since the last report, China has restricted the export of antimony, a metal crucial in the defence sector. This has impacted Europe's ability to supply ammunition to Ukraine.

1.1 Scope of work

This report is the second of three reports that evaluate how Nordic countries can help the EU reach the benchmarks for a more resource-efficient use of critical raw materials (CRM) set by the Critical Raw Materials Act.

This report presents a more in-depth view of a selected number of waste streams and possible recycling options.

3. EU Critical Raw Material Act.

4. <https://www.un.org/en/climatechange/critical-minerals>

1.1.1 Methodology

16 measures were selected for a more thorough evaluation after a dialogue with representatives from the Nordic countries.

1.2 Recycling of critical raw materials (CRM)

The EU defines critical raw materials (CRMs) as materials of high economic importance associated with a high supply risk. The CRMA also defines a group of raw materials as strategic (SRMs). All strategic raw materials listed in 2024 are CRMs, but not all CRMs are considered strategic. Table 1.1 provides an overview of CRMs and SRMs. It summarises key applications and producing countries (including refinery capacity), and estimated total annual global production of primary CRMs. The table also includes the expected annual growth rate (CAGR) for CRM consumption and recycling rates (EOL-RIR). Additionally, Table 1.1 indicates which CRMs currently have Nordic production or recycling operations. A "YES" in brackets indicate marginal production volumes or operations in early phases.

Table 1.1 Critical and strategic raw materials defined by EU. An Asterix indicates that Nordic secondary production exists. Data source: rmis.jrc.ec.europa.eu/rmp

Critical raw materials	Strategic raw material	Applications	Largest producer inc. refining	Nordic production or recycling operations?	Global annual production 2021 (tonnes)	CAGR (%)	EOL-RIR (%)
Antimony	No	Flame retardant, lead batteries, lead alloys, plastic, glass & ceramics	China, Tajikistan	Yes*	94,000	-5	28
Arsenic	No	Zn production, glassmaking, chemicals, alloys and electronics	China Peru	No	55,000	3.7	0
Bauxite/Alumina/Aluminium	Yes	Automotive and other transport, construction, packaging, engineering, consumer durables	Australia, Guinea, China	Yes*	67,669,000	4.3	21
Baryte	No	Drilling fluid, rubber and plastic, chemicals	India, China, Kazakhstan	(Yes)*	8,369,000	-2.4	0
Beryllium	No	Telecom & electronics, industrial components, aerospace & defence	USA, China	No	272	0.4	0
Bismuth	Yes	Chemicals, fusible alloys, metallurgy	China, Vietnam	No	21,000	1.8	0
Boron	Yes	Glass & fiberglass, frits and ceramics, fertilisers, chemicals, construction	Turkey	No	4,920,000	-0.2	1
Cobalt	Yes	Batteries, super alloys, hard metals, catalysts	DR Congo, China	Yes*	166,000	7.3	22
Coking coal	No	Iron & steel production, industrial use, chemicals	China, Australia	No	1,056,000,000	0.4	0

Copper	Yes	Construction, electronics and electrical, industrial, transport, consumer goods	Chile, Peru, DR Congo, China	Yes*	24,949,000	2.5	30
Feldspar	No	Bricks & tiles, ceramics, glass	Turkey	No	36,453,000	4.3	
Fluorspar	No	Steelmaking, fluorchemicals refrigerants & coating, primary aluminium production,	China	(Yes)*	8,391,000	2.1	1
Gallium	Yes	Integrated circuits, opto-electronics, sensors, magnets, PV	China	No	434	4.3	0
Germanium	Yes	Infrared optics, optical fibres	China	No	179	2.6	2
Graphite	Yes	Refractories, batteries, friction material, Lubricants	China	Yes*	1,253,000	2.2	3
Hafnium	No	Super alloys, plasma cutting, nuclear control rods, catalysts	France, USA	No	70	0	ND
Helium	No	MRI &NMR, controlled atmosphere, lifting gas, analytical gas, welding gas	USA, Qatar	No	164 MSm3	-0.6	1
Heavy Rare Earth Elements (Dysprosium)	Yes	Magnets	China, Myanmar, Australia	Yes	3,100	8.8	ND
Heavy Rare Earth Elements (Erbium)	No	Glass	China, Myanmar, Australia	Yes	1,700	8.4	ND
Heavy Rare Earth Elements (Holmium)	No	Magnets	China, Australia	Yes	400	3.7	ND

Heavy Rare Earth Elements (Lutetium)	No	Phosphors	China, Australia	Yes	150	1.4	ND
Heavy Rare Earth Elements (Terbium)	Yes	Magnets, phosphors	China, Myanmar, Australia	Yes	700	9.1	ND
Heavy Rare Earth Elements (Thulium)	No	Phosphors, glass	China, Australia	Yes	150	3.8	ND
Heavy Rare Earth Elements (Ytterbium)	No	Glass	China, Australia	Yes	1,000	4.8	ND
Heavy Rare Earth Elements (Yttrium)	No	Ceramics, phosphors	China, Myanmar, Australia	Yes	19,000	7.6	ND
Light Rare Earth Elements (Cerium)	Yes	Catalysts (aut & FCC), metallurgical, polishing powder, magnets, glass	China, USA	Yes	106,500	9.7	ND
Light Rare Earth Elements (Europium)	No	Phosphors	China, Myanmar, Australia	Yes	900	10.6	ND
Light Rare Earth Elements (Gadolinium)	Yes	Magnets, metallurgical, glass, phosphors	China, Myanmar, Australia	Yes	5,100	10.2	ND
Light Rare Earth Elements (Lanthanum)	No	Catalysts (FCC), metallurgical, polishing powder	China, Myanmar, Australia	Yes	73,500	11	ND
Light Rare Earth Elements (Neodymium)	Yes	Magnets, catalyst	China	Yes	47,500	10.3	1

Light Rare Earth Elements (Praesodymium)	Yes	Magnets, pigments, metallurgical, ceramics	China	Yes	15,000	10.2	ND
Light Rare Earth Elements (Samarium)	Yes	Magnets	China, Myanmar, Australia	Yes	5500	11.7	ND
Lithium	Yes	Glass & ceramics, batteries, lubricants & greases, continuous casting	Australia, Chile	(Yes)	339000	13.8	0
Magnesium	Yes	Automotive, packaging (Al-alloys), pig iron, construction, Mg powder	China	No	1,057,000	2.5	7
Manganese	Yes	Steel	South Africa, Gabon, Australia, China	Yes	21,219,000	1.8	9
Nickel - battery grade	Yes	Steel, CU-alloys, plating, batteries	Indonesia, Philippines, China	Yes*	2,658,000	5	16
Niobium	No	Steel	Brasil	No	122,000	5.7	0
Phosphate rock	No	Fertilisers, food additives, detergents	China, Morocco	(Yes)*	75,371,000	1.8	17
Phosphorous	No	Plastic industry, food industry, water treatment, metal treatment, pharmaceuticals	China	No	1,156	ND	0
Platinum Group Metals (Iridium)	Yes	Electronics, chemical, medical, automotive	South Africa	Yes*	8	-2.2	16
Platinum Group Metals (Palladium)	Yes	Autocatalysts, electronics, chemical, dental & biomedical, jewellery	South Africa, Russia	Yes*	318	0.5	33

Platinum Group Metals (Platinum)	Yes	Autocatalysts, jewellery, chemical, medical & biomedical	South Africa	Yes*	246	-0.7	25
Platinum Group Metals (Rhodium)	Yes	Autocatalysts, chemical, glass	South Africa	Yes*	36	1.4	36
Platinum Group Metals (Ruthenium)	Yes	Electronics, chemical, electrochemical	South Africa	Yes*	34	-1.6	6
Scandium	No	Aluminum alloys, SOFC	China, Japan	No	20	ND	0
Silicon metall	Yes	Aluminum alloys, chemicals, electronics	China	Yes	3,285,000	4.1	0
Strontium	No	Magnets, pyrotechnics, Zn-production, alloys, pigments and fillers	Spain, Iran	No	584,000	5.8	0
Tantalum	No	Capacitators, superalloys, mill products, sputtering targets, carbides	DR Congo, Brasil, Rwanda	No	2,243	7.3	13
Titanium metal	Yes	Aerospace, industrial equipment, defence, consumer products	China, Japan, Russia	Yes	244,000	2	6
Tungsten	Yes	Carbide, metal, alloys, chemicals	China	(Yes)	101,000	3.3	42
Vanadium	No	Steel, alloys, chemicals	China	(Yes)*	116,000	5.2	1

Until around 1890, more than half of the global mining production occurred in Europe. Today, although Europe accounts for only 3–4% of the global mining products, the consumption is nearly ten times greater.^[5] All CRMs consumed in Europe eventually become waste, which may, in some cases, be recycled. The large consumption of CRM-containing products and materials in Europe and the Nordics leads to correspondingly large waste streams, from which CRMs can potentially be recovered. Therefore, recycling should be considered an essential part of the strategy to address the growing CRM supply risks in Europe and the Nordics. However, future CRM needs cannot be covered by recycling alone.

European CRM-recycling projects face a range of challenges, including limited access to capital and uncertain, fluctuating and heterogeneous feedstock. In addition to regulatory barriers, there is a lack of necessary process technology, competence and skilled workforce. In order to increase CRM-recycling in Europe and the Nordics, these challenges must be addressed through appropriate measures and market instruments.

Recycling of CRMs means that waste streams that contain recoverable levels of one or several CRMs are collected, prepared for recycling and used as feedstock in a recycling process that recovers CRM as a new secondary raw material. The Theoretical Recycling Potential (TRP) refers to the maximum amount of critical raw material that can be recovered from a waste stream and is given as the product of the amount of available waste and the mean CRM concentration in the waste stream, as shown in the following equation:

$$TRP = \text{Available waste (tonnes)} \times \text{Mean CRM concentration in waste} \left(\frac{\text{kg}}{\text{tonnes}} \right) \quad (1.1)$$

Due to unavoidable material loss throughout the product life and waste treatment, some CRM materials will not reach recycling operations, as illustrated in Figure 1.1. Because no known recycling process achieves a 100% recovery rate due to technical and thermodynamic limitations, some CRM will also be lost during this operation. CRM-recovery rates between different stages in the product life are described by various terms, as shown in Figure 1.1, and will always be less than 100%. The relative amount of discarded products and materials collected as waste is called the *End-Of-Life - Collection Rate* (EOL-CR). The relative amount of waste delivered to recycling operations is referred to as *End-Of-Life - Recycling Rate* (EOL-RR). The relative amount of CRM recovered from the waste feedstock during recycling is called *End-Of-Life - Recovery Rate* (EOL-R). Finally, the relative amount of CRM that enters as a secondary material into a new product life is referred to as *End-Of-Life - Recycling Input Rate* (EOL-RIR). In other words, the EOL-RIR can be described as the accumulated recovery during EOL-CR, EOL-RR and EOL-R.

5. Utmaningar för att möta ökade behov av metaller och mineral Rapport inom IVAs projekt Vägval för metaller och mineral, 2024.

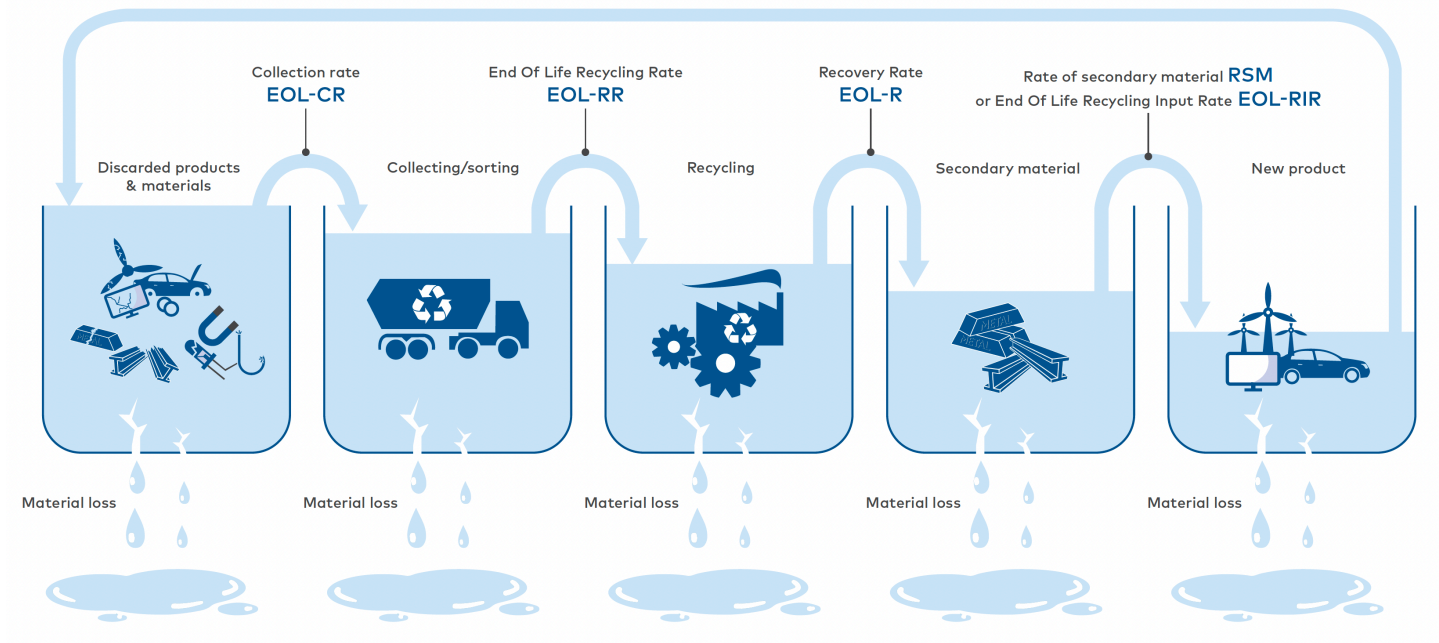


Figure 1.1 CRM-material loss during different stages of the product life. Illustration: Bergfald Miljørådgivere.

Measures and instruments aimed at increasing CRM-recycling should contribute to reduced material loss at one or more stages in the product life, as illustrated in Figure 1.2. For instance, reducing aluminium loss to dross in an aluminium recycling furnace is just as important for achieving the overall recycling target as increasing collection of waste feedstock. Indeed, all parts of a circular value chain require proper attention and an operational framework.

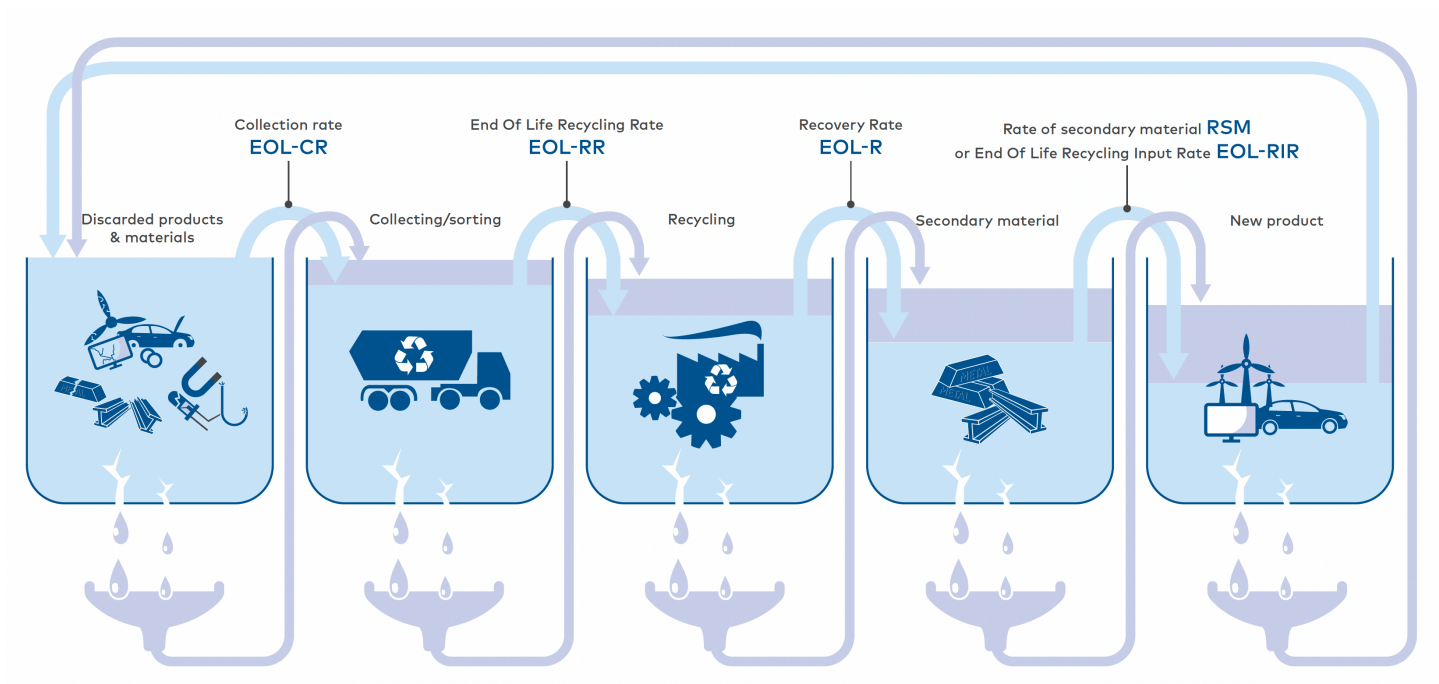


Figure 1.2 The intended effect of instruments and measures designed to increase CRM-recycling. Illustration: Bergfald Miljørådgivere.

In addition to the quantitative perspective on increasing the CRMs recovery rate, there is also a qualitative aspect where the purity of recycled materials compared to virgin equivalents are addressed. Downcycling occurs when recycling processes result in secondary products of lower quality that allow for fewer applications than their equivalent primary product alternatives. Downcycling can also result from insufficient recycling processes that cannot match the same quality as virgin equivalents or from poor sorting and pretreatment of waste material used as feedstock for the recycling operation. This is illustrated in Figure 1.3. For instance, when metal from a car is shredded initially with little or no separation of primary alloys, the material fractions that are sorted contain high levels of mixed materials and alloys. Ideally, these should be recycled separately. Instead, these mixed materials, including many CRMs, often go into a single smelting process, where most components end up as pollutants of the resulting secondary raw material or are lost in slag or other waste residues. This scenario is illustrated in the upper pathway of Figure 1.3. In contrast, if the car is more thoroughly separated into individual parts with homogenous chemical composition, as shown in the lower pathway of Figure 1.3, recycling operations can produce materials with significantly higher quality, often closer to the primary products.

Better sorting and pretreatment are often more expensive and labour-intensive as they may require manual separation or cutting of components with similar chemical compositions. They also involve removing electrical and electronic components that would otherwise be shredded with metal scrap, resulting in a mechanical mixture of various CRMs. However, improved sorting and pretreatment may significantly increase both the recovery rate and quality of recycled CRM products. Thus, measures and instruments to facilitate such a development should be considered an essential part of any CRM-recycling strategy.

A car typically consists of approximately 50 different metals, many of which are CRMs. Improved manual pretreatment prior to shredding can enhance the separation of individual alloys with distinctive chemical compositions, along with magnets and other electrical components, which should be recycled separately. Such pretreatment can also be made more effective through vehicle design that facilitates easy separation and enables straightforward removal of electrical components.

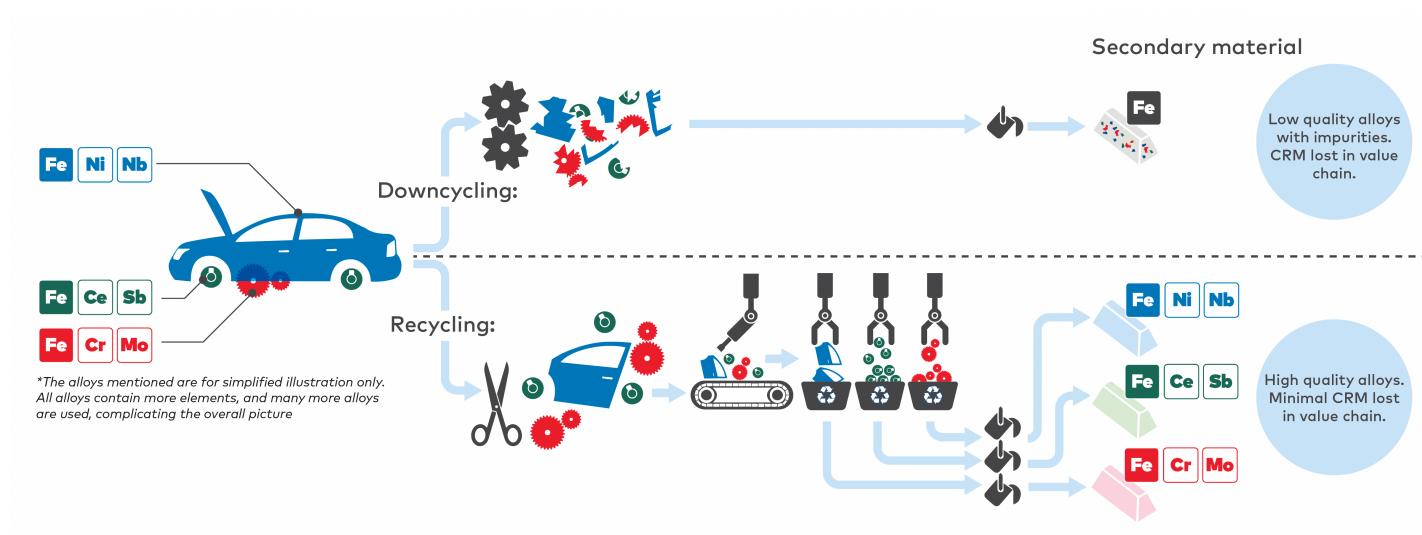


Figure 1.3 Careful sorting and pretreatment of waste used as feedstock in a recycling operation may improve the quality of resulting secondary CRM-products. Illustration: Bergfald Miljørådgivere.

*The alloys mentioned are for simplified illustration only. All alloys contain more elements, and many more alloys are used, complicating the overall picture.

Suboptimal pretreatment prevents efficient CRM-recycling in Europe and the Nordics. While more careful pretreatment is possible, technical and economic barriers currently stand in the way. Because advanced solutions for disassembly and high-quality sorting of scrapped cars, WEEE and other CRM-intensive waste streams have yet to be fully developed such operations currently rely heavily on manual labour, which is both expensive and time-consuming. Furthermore, regulatory mechanisms that compensate for additional costs regarding high-quality sorting and pretreatment have yet to be introduced, making such solutions less competitive in the market.

The two most common CRM-recycling technologies are pyrometallurgical and hydrometallurgical extraction. Pyrometallurgical extraction typically involves introducing the CRM waste, used as feedstock, into a furnace that separates the CRMs from other chemical constituents. In contrast, hydrometallurgical extraction generally entails dissolving the waste material in acid, followed by the separation of CRMs through various chemical methods. The recycling of certain CRMs can be particularly challenging compared to others. European and Nordic CRM-recycling faces limitations due to economic, technical and regulatory barriers which are summarised in the first report and will be further addressed in this report through discussions of potential measures and instruments

1.2.1 CRM-recycling benchmarks set by the EUs critical raw materials act

The Critical Raw Materials Act (CRMA) came into effect on May 23, 2024, aiming to ensure the EU access to a secure, resilient and sustainable supply of critical raw materials. Promoting resource efficiency and circularity throughout the value chains is emphasised as a central strategy towards achieving this objective.

Article 5 of the CRMA sets several benchmarks for future CRM production capacities in the EU, covering CRM extraction, processing and recycling. As illustrated in Figure 1.4, by 2030 EU's CRM-extraction capacity shall meet at least 10 % of its total annual consumption of strategic raw materials (see Table 1.1 for CRMs). Within the same timeframe, EU processing capacity, including all intermediate steps, must account for at least 40% of its annual consumption of strategic raw materials. At the same time, the EU must establish a recycling capacity capable of meeting at least 25% of its annual SRM consumption, also considering all intermediate recycling steps.

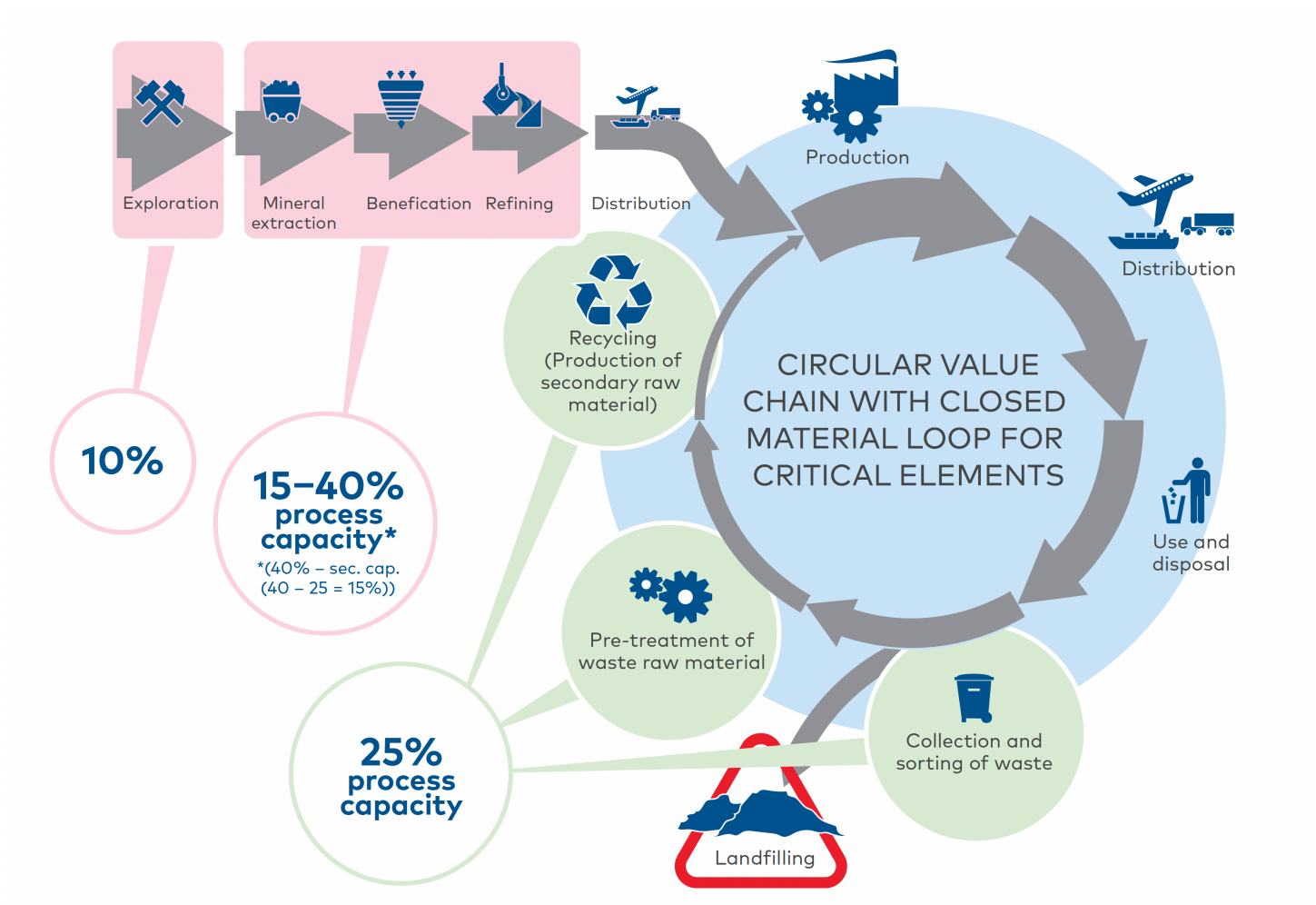


Figure 1.4 CRMA capacity benchmarks for SRM-value chains within 2030. Illustration: Bergfald Miljørådgivere.

Figure 1.5 provides an overview of the current recycling status for various critical raw materials compared to the 25% capacity goal set for 2030. Although all CRMs are included in the illustration, the capacity goal specifically applies to the CRM subgroup of strategic raw materials (SRMs). The diagram indicates that only four CRMs currently meet the 25% capacity requirement: tungsten, copper, PGMs and antimony.^[6] European recycling solutions are also relatively well developed for nine additional CRMs including cobalt, aluminium, titanium, phosphate rock, nickel, tantalum, feldspar, manganese and magnesium, although most of these cases involve downcycling. For the remaining 21 CRMs, the European recycling capacity is either marginal (<5%) or non-existent.

When considering CRMs that currently lack established recycling options in Europe, it is important to understand that absence is often due to unfavourable market conditions, which make such operations unprofitable. However, in some cases, it stems from the lack of commercially viable recycling technologies, meaning no recycling operations can be established, even with political mandates. For secondary CRM value chains where relevant process technology is unavailable, substantial R&D efforts will be necessary to develop these solutions.

6. Antimony has its high recycling rate due to its use as alloying element in lead accumulators. Extraction of pure antimony from lead is costly and current not performed in Europe.

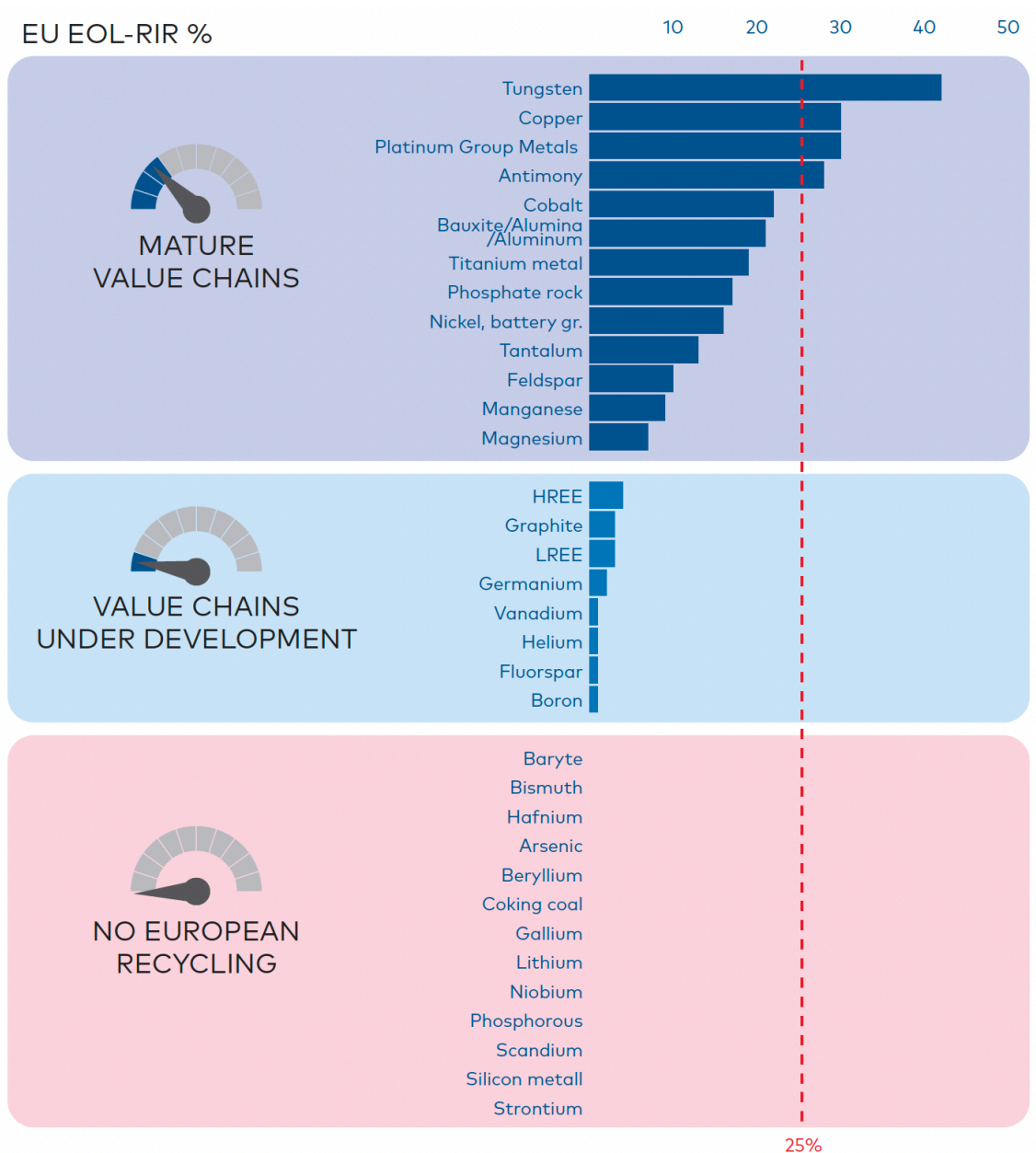


Figure 1.5 Current EOL-recycling input rates compared to the CRMA 25% recycling benchmark for 2030. Data source: rmis.jrc.ec.europa.eu/rmp. Illustration: Bergfald Miljørådgivere.

Compared to more developed secondary CRM value chains that currently maintain a relatively high rate of CRM-recycling, less developed secondary CRM value chains may require distinct support mechanisms to reach the CRMA 25% recycling benchmark, as illustrated in Figure 1.6.^[7] For secondary CRM value chains with available recycling capacity, the primary focus should be on implementing measures and instruments to enhance the collection and pre-treatment of waste streams that can serve as feedstock for the recycling processes. Conversely, for CRMs lacking existing recycling capacity, the focus should shift towards establishing collection schemes for relevant waste streams in anticipation of new recycling options becoming available in the future.

7. The 25% benchmark in CRMA formally only applies to strategic raw materials which per 2024 includes bismuth, boron, cobalt, copper, gallium, germanium, lithium, magnesium, manganese, natural graphite, nickel, PGMs, magnetic REE, silicon- and titanium metal and tungsten. All these materials are also classified as critical. CRMA does however encourage increased recycling for all critical raw materials, and the 25% benchmark can therefore be used as a voluntary target, although not legally binding.

For secondary CRM value chains with limited process capacity, the main strategy would likely benefit from focusing on identifying and demonstrating the best available recycling technology options and supporting recycling projects in the early development phases.

For CRMs and relevant waste streams where no recycling technology is currently available, substantial R&D efforts should be prioritised to drive innovation in this direction.

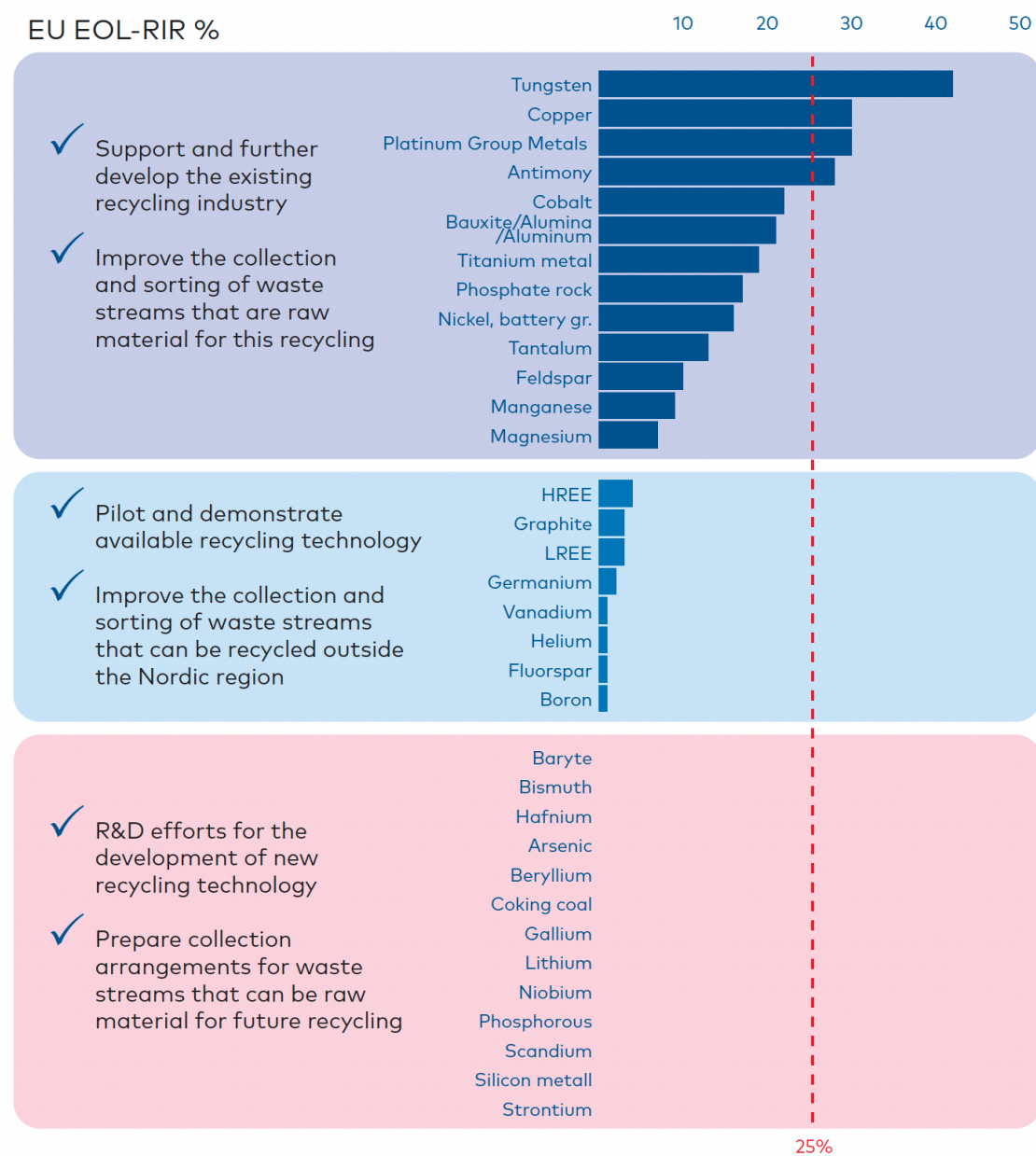


Figure 1.6 Different perspectives and considerations when designing support mechanisms for individual secondary CRM-value chains that differ in development maturity. Illustration: Bergfald Miljørådgivere.

1.2.2 Other EU-legislation with impact on CRM-recycling

In addition to the CRMA, several other EU regulations affect the framework conditions for CRM recycling. The most critical regulations in this regard are the following:

- Waste Framework Directive
- Extractive Waste Directive
- WEEE Directive
- Battery Directive
- End of Life Vehicle Regulation
- The Eco-design for Sustainable Products Regulation (ESPR)

Waste Framework Directive

The European Waste Framework Directive sets the basic concepts and definitions related to waste management. It requires a national waste policy where these treatments are given priority according to the waste hierarchy. The directive lists the following methods as part of the hierarchy:

- a. prevention
- b. preparing for re-use
- c. recycling
- d. other recovery, e.g. energy recovery
- e. disposal

The directive requires member states to take measures to encourage the options that deliver the best overall environmental outcome.

The directive also defines the boundaries between waste and by-products while proposing guidelines for End of waste criteria. These are significant for CRMA-recycling and secondary CRM products, as they establish quality standards for when recycled CRMs from waste can be considered a secondary product.

The directive also provides overall guidelines for Extended Producer Responsibilities (EPR), which regulate the EPR schemes that are responsible for important CRM-waste streams like scrapped cars, WEEE and batteries. Additionally, individual EPR schemes are governed by more specific regulations found in separate EU directives.

The directive requires member states to establish national waste management plans that include measures to improve environmentally sound preparations for re-use, recycling, recovery and disposal of waste. These measures will clearly overlap with the national program for CRM recycling and other risk-reducing measures for CRM supply lines. As a result, both plans may be integrated into a single document.

Unlike EU regulations like the Battery Directive or CRMA, the Waste Framework Directive does not include substance-specific recycling benchmarks for individual chemical elements. Instead, it focuses on more broadly defined waste categories such as plastic, metals and others.

Extractive Waste Directive

While the Extractive Waste Directive mainly focuses on the safe disposal of non-useable minerals, the directive also requires operators to perform proper characterisation of the composition. Minor concentrations of CRM minerals may occasionally be present in extractive waste. Thus, such characterisation is the first line of defence to prevent landfilling of CRMs that could be extracted. The directive also emphasises that the recovery should be a focus of all extractive waste management plans.

WEEE Directive

The first version of the WEEE Directive entered into force in 2003 and has since been updated several times. The EU is currently evaluating the need for further revisions.^[8]

The directive describes required measures to reduce the adverse impacts of the generation and management of Waste from Electrical and Electronic Equipment (WEEE). The directive covers regulations regarding product design, waste collection and collection rates, treatment facilities and recovery rates. The current version of the directive contains overall benchmarks for recovery and preparation for reuse and recycling. However, unlike the Battery regulation and ELV regulation, recycling benchmarks for specific CRMs are not included.

The Battery regulation

On August 17th 2023, the new Batteries Regulation of the EU entered into force, thus replacing the Battery directive from 2006.^[9] The new regulation includes provisions on sustainability, safety, labelling, marking, and information to facilitate the placing of batteries on the market or putting them into service within the Union. It also sets minimum requirements for extended producer responsibility, the collection and treatment of waste batteries, and reporting. All these form an essential part of the total framework conditions under which Nordic CRM-recycling from batteries will operate.

The regulation applies to all categories of batteries, including portable batteries, Starting, Lighting and Ignition batteries (SLI batteries), Light Means of Transport (LMT) batteries, electric vehicle batteries and industrial batteries. It also covers batteries that are incorporated into or added to products, or that are specifically designed to be incorporated into or added to products.

Article 11 of the regulations introduces requirements for the removability and replaceability of portable batteries and LMT batteries. These requirements will also benefit CRM-recycling operations as they allow easier and more cost-effective dismantling of the battery component from the product. Furthermore, they prohibit the use of welding and glued connections, which make disassembly challenging and time-consuming.

The regulation also contains requirements for minimum shares of secondary CRM-battery materials like lithium, cobalt and nickel in new batteries that are placed on the European market.

Article 70 prohibits end disposal like landfilling or incineration, which render discarded batteries unavailable for recycling. In contrast, Article 71 outlines benchmarks for the efficiency of recycling and the recovery of materials in battery recycling operations. Within 2027, all European battery recycling operations are required to achieve a recycling efficiency of at least 90% for cobalt, copper and nickel, and 50% for lithium. By 2030, these requirements will be increased to 95% and 80%, respectively.^[10]

8. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en#timeline

9. https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en

10. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542>

The Battery regulation also requires all batteries above a minimum size to be associated with a battery passport that is interoperable with other digital product passports required by the Eco design directive. The passport and battery labelling will include information about CRMs present in the battery.

End-of-Life Vehicle Regulation

The End-of-Life Vehicle Regulation (ELV Regulation) contains regulations regarding the treatment of scrapped vehicles and their components. It includes circularity requirements related to the design and production of the vehicles, focusing on aspects such as reusability, recyclability and recoverability. Furthermore, the regulation mandates the use of recycled content, which must be verified during the type-approval process of vehicles. It also outlines information and labelling requirements for parts, components and materials used in vehicles. The regulation lays down requirements on extended producer responsibility, as well as the collection and treatment of end-of-life vehicles, including the export of used vehicles from the EU to third countries. Among these requirements are design standards that facilitate the easy removal and replacement of recyclable parts and components, as well as the mandatory removal of certain parts and components to enhance the efficiency of CRM recycling.

Article 4 of the regulation requires new vehicles to be designed and constructed to allow for reuse or recycling to a minimum of 85% by mass, and recovery of at least 95% by mass. Article 6 states that, following a feasibility study, the Commission may introduce minimum recyclability shares for CRMs such as aluminium, magnesium and REE in the coming years.

Article 13 requires all new vehicles to have a digital passport similar to equivalent passports required by the Battery Directive and Eco-design regulation.

A proposal for a revised directive was presented in 2023 and has yet to be adopted. The proposal is supposed to replace not only the existing ELV directive but also several other directives, including the *Directive on the type-approval of motor vehicles regarding their reusability, recyclability and recoverability*.^[11]

The Eco-design for Sustainable Products Regulation (ESPR)

The Eco-design for Sustainable Products Regulation (ESPR) entered into force on July 18th 2024 and is the primary legislative initiative of the EU towards more environmentally sustainable and circular products.^[12]

The regulation defines *Eco-design* as *the integration of environmental sustainability considerations into the characteristics of a product and the processes taking place throughout the product's value chain*.

The regulation provides a framework for eco-design requirements that products must fulfil to be placed on the European market or put into service. The regulation also provides guidelines for a digital product passport and mandatory green public procurement requirements. The regulation also sets up a framework to prevent unsold consumer products from being destroyed.

The ESPR requires that products, components and materials covered by the regulation be associated with a digital product passport. This passport must contain accurate, complete and

11. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02005L0064-20090203>

12. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

up-to-date information as described in ESPR and its delegated acts. The goal is to support the sustainability and circularity of the products while also strengthening their legal compliance. The information included will cover manuals on disassembling products for repair and recycling. A final and detailed description of the required data for the digital passport will be provided by the EU Commission at a later stage.^[13] The final format for the digital passport is expected to include information about:

- Product's technical performance
- Materials and their origins
- Repair activities
- Recycling capabilities
- Lifecycle environmental impacts

CRM recycling is often limited by incomplete information about the chemical composition of waste materials. The best possible treatment of these materials is to achieve optimal CRM-recovery safely. A digital passport can potentially be an important tool for better sorting and recycling procedures by making this information more readily available.

1.3 Socio-economic consequences of CRM-recycling

CRM recycling has socioeconomic effects on many levels of society. The most important of these is the potential for increased self-sufficiency in recycled materials. Without access to the critical raw material, modern society, as we know it, would face severe disruptions. Key sectors such as electronics, transportation, industry and defence would come to a standstill. Recycling CRMs will reduce the risk and consequence of external supply limitations. Indeed, increased CRM-recycling will make society safer and more resilient, reducing stress and uncertainties of the future.

Raw materials carry a societal significance comparable to energy, as they are the building blocks that all products and materials around us are based on. Without raw materials, there are very few ways to utilise energy. Access to enough necessary raw materials is therefore essential for sustained industrial production and value creation, as well as to ensure that crucial human needs can be met and critical welfare schemes can be upheld.

Since the EU first announced its plan to introduce a regulation on CRMs in 2023, the rationale for increased efforts towards reducing CRM supply risks is becoming even more abundantly clear. Modern society relies heavily on products and services that require CRMs as an input, and a disruption in the value chains that supply these CRMs will damage downstream industries that require CRMs as feedstock for further production and may lead to disruption or collapse in living conditions and welfare schemes that are expected in modern society. Figure 1.7 summarises factors that are causing increased supply risks for most CRMs.

13. https://green-business.ec.europa.eu/implementing-ecodesign-sustainable-products-regulation_en



Figure 1.7 Factors that is causing increased CRM-supply risks. Illustration: Bergfald Miljørådgivere.

As the global human population and the GDP of most countries continue to grow, CRM consumption increases correspondingly. This CRM consumption growth is accelerated further by technology shifts regarding the de-fossilisation and digitalisation of the economy, which both require increased CRM inputs compared to the technology platforms they replace. Renewable energy production like wind turbines and solar panels, together with electrification of the transport sector, is expected to multiply the need for CRMs such as silicon, gallium, lithium, nickel and rare-earth metals in the coming years. In contrast, the current consumption rates are far beyond the expected growth rate of many other raw materials.

At the same time, because the extraction of minerals for economic reasons is always based on the richest available ores, over time, this leads to decreasing CRM levels in remaining ore reserves, increasing relative costs and environmental footprints for future primary CRM production.

There is also a declining social acceptance of mining operations in many countries, not only in the developed world but also in several countries that today are crucial providers of many CRMs.

Another supply concern is increasing protectionism and trade restrictions on exporting raw materials from important suppliers of CRMs. Taken as a whole, this situation would alone be cause for high concern but is aggravated further by ongoing wars in Ukraine and the Middle East, together with rising tensions between China, Russia and the US leading to a destabilised security situation and threatened trade routes like the important passage through the Red Sea. Increasing extreme weather and other undesirable climate events can also be added to the list of issues that threaten future CRM supply.

1.4 Environmental consequences of CRM-recycling

CRM-production at different stages of the value chain creates impacts on the environment that may be climatic or affect water, soil, fauna or flora, and these effects must be considered when setting up new or expanding existing CRM value chains. Although the production of both primary and secondary CRMs has unfavourable or detrimental environmental impacts, the overall footprint of primary production will most often be more extensive than that of similar amounts of secondary CRM.

A quantitative comparison of the total environmental footprint from primary and secondary CRM-production for a specific CRM is possible through a life cycle assessment. However, this requires knowledge about what type of technology and process techniques are applied at each step for both value chains and involves complex calculations that go beyond the mandate of this project. Some semi-quantitative statements can be made, though, regarding differences in environmental footprints between value chains for primary and secondary CRMs.

The negative from the secondary CRM-production footprint is mainly due to the consumption of energy and chemicals used as input during the collection and preparation of selected waste streams and later during the recycling process, in addition to emissions and waste materials generated during the same process steps.

Unlike the production of secondary CRM, almost all primary CRM materials are based on ore mining and processed through a series of steps that include ore dressing and further refining. For many CRMs, the materials are extracted as a byproduct to a primary ore, such as gallium from aluminium ore or germanium from zinc ores, which limits process parameters and volumes to the primary ores (in the mentioned examples; aluminium and zinc). Mined mineral ores often disrupt large areas, both during ore excavation and later when waste minerals from ore dressing are deposited in landfills.

Landfilling waste minerals covers areas where immobile biological life will be eliminated when buried in sediments. Mineral particles from the landfill may also be transported to the surroundings and cause unwanted effects. Particle loss may happen through dust dispersion, run-off water or dam failure.

Run-off water is sometimes acidic and may contain dissolved heavy metals and residual chemicals from the ore dressing process. Mining operations also often require a large consumption of water and chemicals and much energy to move, crush and mill the ore, as well as to separate valuable minerals from the remaining waste minerals.

Processing ore concentrate through either pyrometallurgical, or hydrometallurgical methods requires substantial energy inputs (often both electricity and coal/coke) and chemicals, generating significant waste in the form of slag and dust that must undergo waste treatment. Hydrometallurgical processes typically consume less energy than pyrometallurgical methods but may be chemical-intensive. Pyrometallurgical processes, however, also require chemical inputs such as flux and slag formers.

When secondary CRMs replace primary CRMs, the environmental footprint of primary production is eliminated and typically replaced by a smaller footprint from secondary production processes. Collecting and preparing waste streams for CRM recycling may require additional energy compared to the standard end treatment for these wastes. However, recycling generally reduces the amount of residual waste needing landfilling and, if it replaces incineration, eliminates related emissions and ash production. While the CRM recycling process consumes significant amounts of energy and often chemicals, these requirements are typically much lower than those of primary production. For instance, secondary aluminium production consumes only about a tenth of the energy required to produce the same amount of primary aluminium. The exact environmental footprint of a specific CRM-recycling process depends on various factors, including the type of CRM being recycled, waste feedstock, the technology employed, and the quality standards of the final product.

Just as many virgin ores are contaminated with environmental toxins, so are many fractions of secondary CRMs. WEEE commonly contains high concentrations of lead and minor levels of beryllium, thallium and mercury. Post-consumer products may contain organic toxins, asbestos, microplastics, synthetic rubber and other materials. These undesirable elements and contaminants may influence the processing of CRM-rich waste but can also result in local emissions or the formation of hazardous waste.

2. Waste streams with CRM-recycling potential

CRM-recycling requires waste streams that can serve as feedstock for the recycling process. The EU Commission has announced that it will, in the near future, publish guidelines on which waste streams to consider for CRM-recycling. In the meantime, this chapter aims to provide a preliminary perspective on this issue. Waste streams relevant to CRM-recycling can be collected at different stages of the material product life, as illustrated in Figure 2.1.

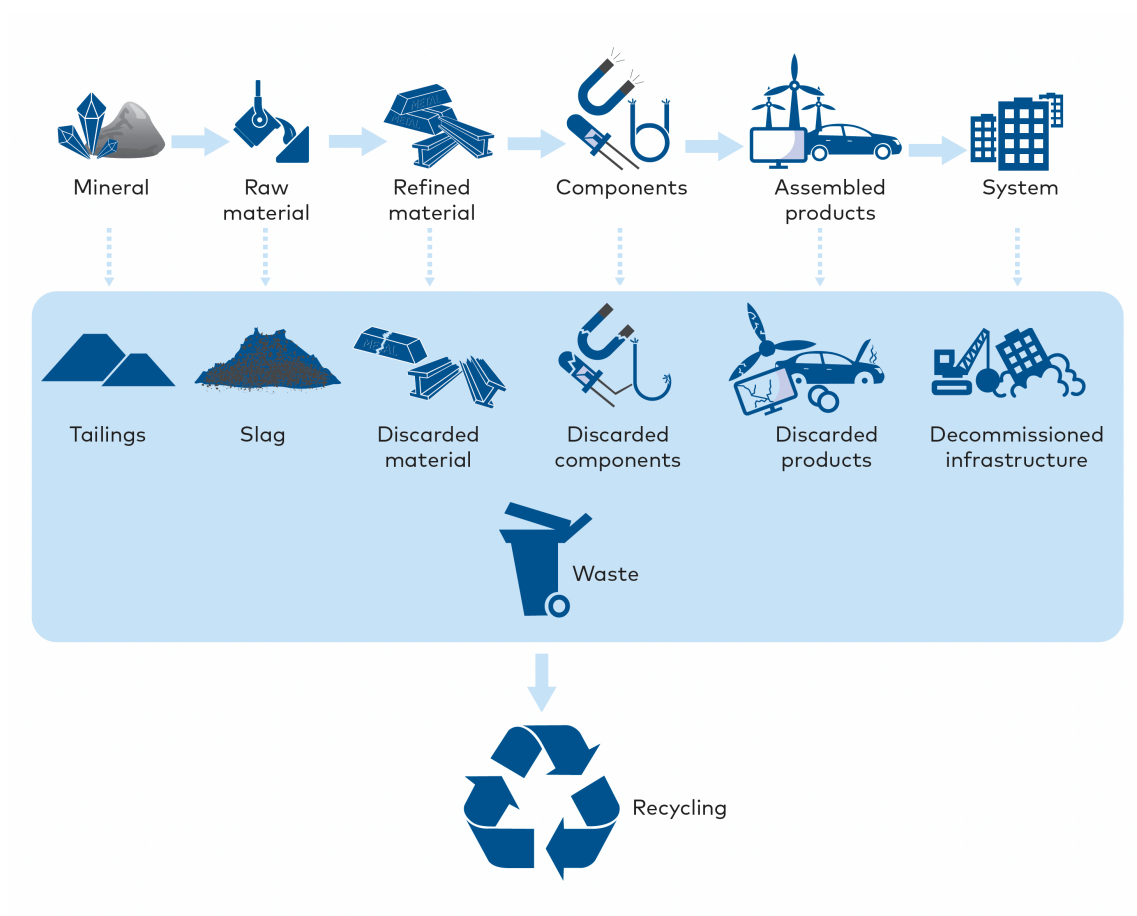


Figure 2.1 Waste streams for CRM-recycling can be collected at different stages of the CRM-materials product life. Illustration: Bergfald Miljørådgivere.

Waste streams that are expected to have CRM-recycling potential include:

Mineral waste streams

- Tailings
- Alum shale

Waste from processing raw materials

- Jarosite
- Electric arc furnace (EAF)-dust
- Steel slag
- Spent pot liner from the production of primary aluminium (SPL)
- Dross, slag and dust from primary aluminium production
- Geothermal brines
- Pyrite ash

Waste from discarded components, assembled products and decommissioned infrastructure and waste treatment

- Mixed WEEE
- Printed circuit boards
- Cables
- LED and screens
- Scrapped vehicles
- Tires
- Batteries
- Fly ash from waste incineration
- Bottom ash from waste incineration
- Ash from the combustion of biomass
- Organic waste

For a waste stream to be profitable to recycle, the value of the CRMs recovered must compensate for the costs of the recycling operation. From an economic perspective, the waste streams containing high concentrations of valuable CRMs will apparently be more profitable to recycle than those with lower concentrations. At a certain threshold, the value obtained from the recovered CRMs will be inadequate to cover the costs of the recycling operation unless there is an external economic compensation for this, for instance, in the form of tariffs on virgin materials or recycling subsidies. Some of these structures are already in place, such as the EPR schemes on electronic components used to collect and sort WEEE.

There is also the market competition from primary CRMs to consider. Unlike primary production, where CRMs are extracted from mineral ore typically located near an ore dressing plant, the recycling process often involves collecting waste material from numerous, geographically dispersed collection sites. Waste streams are typically also more chemically complex and may require more advanced and expensive recovery processes. It can also be challenging to collect enough waste for a recycling process to be scaled for an optimal size where unit costs of production become most favourable.

The recycling costs are often a function of the concentration of the material being recovered. The lower the concentrations, the higher the production costs partly due to increased energy and chemical inputs. If the CRM concentrations in the waste streams are significantly lower than those found in the mineral ores used to produce primary CRMs, the secondary recovery process is often not cost-competitive with similar primary CRM products. Table 2.1 provides estimates of the minimum concentrations of CRM required in a waste stream for recycling to be profitable. These figures are indicative, reflecting historical metal prices from the last decade. It is possible to find waste streams both below and above these indicative levels with opposing conclusions due to specific waste characteristics. Sometimes, a waste stream contains more than one extractable CRM and will, in such cases, provide multiple income streams that can carry the recycling costs. The overall picture is, however, that a large proportion of recoverable CRMs in available waste streams cannot be extracted for economic reasons without targeted incentives.

Table 2.1 Estimated minimum CRM-concentration in waste stream for profitable and environmentally sustainable recycling. Source: Bergfald Miljørådgivere.

Critical raw materials	Minimum concentration for recycling
Antimony	>1%
Arsenic	>10%
Aluminum	> 50% alumina
Baryte	>10%
Beryllium	>10%
Bismuth	>1%
Boron	>10%
Cobalt	>0.2%
Coking coal	Not considered relevant
Copper	>0.3%
Feldspar	>50%
Fluorspar	>2%
Gallium	>100 ppm
Germanium	>100 ppm
Graphite	>15%

Hafnium	>2%
Helium	
Heavy Rare Earth Elements (Dysprosium)	>100 ppm
Heavy Rare Earth Elements (Erbium)	>1%
Heavy Rare Earth Elements (Holmium)	>0.5%
Heavy Rare Earth Elements (Lutetium)	>50 ppm
Heavy Rare Earth Elements (Terbium)	>50 ppm
Heavy Rare Earth Elements (Thulium)	>10%
Heavy Rare Earth Elements (Ytterbium)	>1%
Heavy Rare Earth Elements (Yttrium)	>10%
Light Rare Earth Elements (Cerium)	Overproduction currently being landfilled
Light Rare Earth Elements (Europium)	>1%
Light Rare Earth Elements (Gadolinium)	>1%
Light Rare Earth Elements (Lanthanum)	>20%
Light Rare Earth Elements (Neodymium)	>1%
Light Rare Earth Elements (Prasodymium)	>0.5%
Light Rare Earth Elements (Samarium)	Overproduction currently being landfilled
Lithium	>1%
Magnesium	Not suitable for magnesium production
Manganese	>30%
Nickel - battery grade	>0.5%
Niobium	>0.2%
Phosphate rock	>2%
Phosphorous	Not considered relevant

Platinum Group Metals (Iridium)	>0.01 ppm
Platinum Group Metals (Palladium)	>0.2 ppm
Platinum Group Metals (Platinum)	>0.5 ppm
Platinum Group Metals (Rhodium)	>50 ppb
Platinum Group Metals (Ruthenium)	>10 ppm
Scandium	>1000 ppm
Silicon metall	>90 %
Strontium	>10%
Tantalum	>100 ppm
Titanium	>10%
Tungsten	>500 ppm
Vanadium	>1%

2.1 Mineral waste streams

Tailings

The extraction of minerals gives rise to vast amounts of waste materials with diverse grain sizes and geological and chemical compositions. Waste rock is rock material removed to provide access to the ore. Sometimes, low-quality ore is landfilled together with the waste rock. Ore dressing or beneficiation is a series of process steps that separate valuable minerals from residual matter called tailings. Depending on the separation efficiency of the beneficiation, varying levels of valuable minerals will remain in the tailings, often including CRMs. Concentrations of CRMs that remain in the tailings, together with the geochemical properties decide whether further extraction of CRM is technically feasible. Total amounts of tailing available for recycling and logistic costs are important factors that further decide if CRM-recovery is economically viable.

Currently, several base metals mined in the Nordics, such as iron and copper, have minor CRMs in associated minerals. These are slightly enriched and more available when the ore is crushed, milled, and base metals are extracted.

Tailings is by far the largest waste stream generated in the Nordic countries, with annual volumes exceeding 100 million tonnes, with Sweden (55 million tonnes) and Finland (40 million tonnes) generating the dominating amounts. In addition, vast deposits of legacy tailings also exist in the Nordics. As the introduction of more advanced ore dressing techniques like flotation and magnetic and gravitational separation have made extraction possible from lower grade ores, historic mineral waste sometimes contains higher levels of residual valuable minerals.

By utilising improved extraction technology, tailings can potentially be reprocessed to extract more of the originally extracted metals that earlier ore dressings were unable to separate. Because the tailings have already been processed, they may contain higher levels of the associated CRMs compared to the original ore.

Nevertheless, almost all mining is done on ore with the highest available content of valuable minerals. The remaining ore in the world is continually diminished, which will, at some point, make some residual levels in tailings or discarded ore relevant for new extraction efforts. At the same time, being sand with optimal grain size and often deposited at a single site saves costs compared to new ore that must be excavated from a mine and crushed and milled down to desired particle sizes. Two examples of such reprocessing are the company Grängex, which is preparing to extract phosphate and REE from 10 million tonnes of tailings deposited in Grängeberg in Bergslagen, Sweden,^[14] and the even larger REE-map project where LKAB prepares a very similar production.^[15] LKAB has recently announced a sizable industrial investment of SEK 800 millions into the extraction of REE and phosphates from their flotation tailing.^[16]

Globally, as the establishment of new mines has been increasingly costly and permitting takes decades – not years, there is a growing trend of reprocessing tailings. After the issue of reprocessing tailings became popular a handful of years ago, we currently see a surge of new technologies and equipment marketed towards this. High energy prices have contributed to the reprocessing trend, as the energy cost of crushing hard rock for mineral extraction is often the single highest operation cost.

With the Nordic legacy of billions of tons of landfilled tailings and annual production of 100 million tonnes, we would assume an increased interest in this sector as a source of CRM-extraction. Leading Nordic mineral processing equipment producers are at least positioning themselves towards this coming market.^[17]

The extraction efficiency of mineral operations is correlated with economic trade-offs. Higher extraction efficiencies entail a more significant consumption of capital goods, energy and chemicals. These increasing costs must be balanced by a corresponding increase in the sales value of the produced minerals to maintain the profitability of the operation, and continued efficiency efforts will eventually result in diminishing economic returns compared to the rise in costs. Increased mineral prices or reduced energy costs will typically increase extraction efficiency. The efficiency of all mining operations can, therefore, be increased, both regarding overall extraction efficiency and concerning the number of chemical components extracted. If necessary, incentives are presented. A typical way to increase extraction efficiency is to add additional process steps, such as introducing an extra flotation step, increasing residual time, increasing water consumption etc. Suppose the mining operation is extracting CRMs such as copper, cobalt or PGMs; an added flotation step will typically increase the extraction efficiency of these components by several hundred parts per million.

Waste generation will equally fall with increased extraction efficiency. Even incremental improvements might reduce landfilled waste volumes by millions of tonnes as less ore needs to be extracted.

14. <https://grangesbergexploration.se/en/operations/grangex-apatite/>

15. <https://lkab.com/en/press/lkab-plans-a-fossil-free-industrial-park-for-recycling-mine-waste-and-producing-critical-raw-materials/>

16. <https://lkab.com/en/press/lkab-takes-the-next-step-in-its-investment-in-critical-minerals/>

17. <https://www.metso.com/insights/blog/mining-and-metals/how-to-generate-value-from-tailings-with-reprocessing-to-be-future-ready/>

Many CRMs are typically found in low concentrations associated with extracted base metals. Due to prohibitive costs, these CRMs are often not extracted as byproducts and, therefore, left in the tailings. Figure 2.2 shows examples of CRMs typically found together with certain base metals. As the figure shows, certain base metals like zinc and lead are often found together in the same ore. The same situation sometimes also occurs for nickel, copper, and zinc. Individual CRMs like cobalt, vanadium and phosphate are commonly found in the ore of several base metals, albeit rarely in high concentrations.

Some of the most promising and profitable CRM projects in the Nordics are based on such extraction. Most important is the LKAB processing of its apatite flotation sludge into high-value phosphate- and REE-feedstocks for further refining inside the Nordic industry.

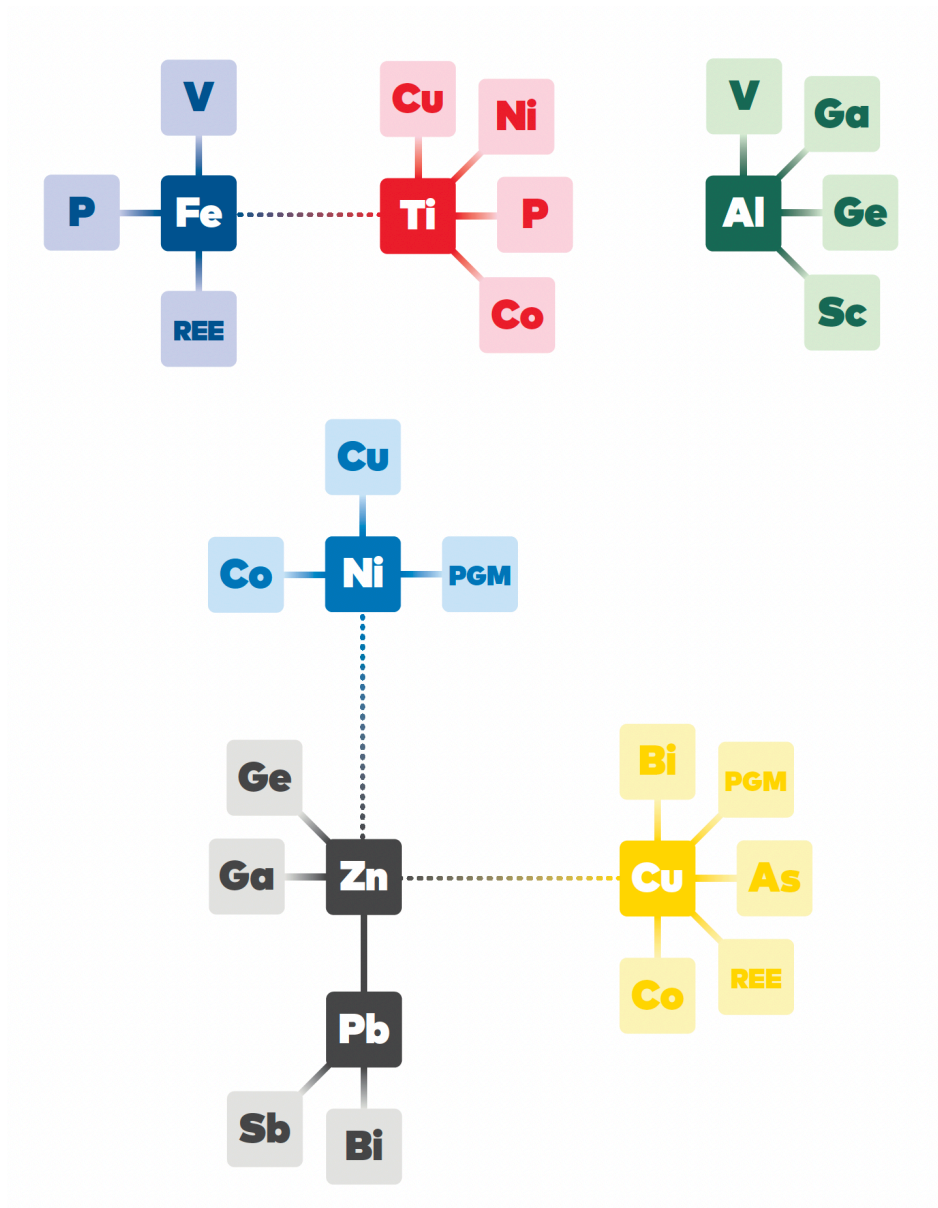


Figure 2.2 Examples of CRMs commonly found as bi components in ore of base metals. Illustration: Bergfald Miljørådgivere.

Table 2.2 shows the range of CRM-concentrations found in Swedish tailings compared to the estimated minimum CRM-concentration in waste streams for profitable and environmentally sustainable recycling. The table also includes typical background concentrations at which the CRMs are found in the earth's crust.

Table 2.2 Range of CRM-concentrations found in Swedish tailings compared to estimated minimum CRM-concentration in waste stream for profitable and environmentally sustainable recycling. Data source: Sveriges geologiska undersökning.

Critical raw materials	Minimum concentration for recycling	Background concentration in the earth's crust	Tailings (ppm)
Antimony	>1%	0.2 ppm	0.8–660
Arsenic	>10%	1.8 ppm	
Aluminum	> 50% alumina	8.2%	
Baryte	>10%	425 ppm	
Beryllium	>10%	3 ppm	0.29–4.9
Bismuth	>1%	0.2 ppm	0.017–29
Boron	>10%	10 ppm	
Cobalt	>0.2%	25 ppm	13–420
Coking coal	Not considered relevant		
Copper	>0.3%	68 ppm	25–5600
Feldspar	>50%		
Fluorspar	>2%	590 ppm	
Gallium	>100 ppm	17 ppm	8.1–35
Germanium	>100 ppm	1,5 ppm	0.17–3.2
Graphite	>15%		
Hafnium	>2%	3 ppm	1.5–4.1

Helium			
Heavy Rare Earth Elements (Dysprosium)	>100 ppm	5.2 ppm	
Heavy Rare Earth Elements (Erbium)	>1%	3.5 ppm	
Heavy Rare Earth Elements (Holmium)	>0.5%	1.3 ppm	
Heavy Rare Earth Elements (Lutetium)	>50 ppm	0.8 ppm	
Heavy Rare Earth Elements (Terbium)	>50 ppm	1.2 ppm	
Heavy Rare Earth Elements (Thulium)	>10%	0.52 ppm	
Heavy Rare Earth Elements (Ytterbium)	>1%	3.2 ppm	
Heavy Rare Earth Elements (Yttrium)	>10%	30 ppm	6.8–120
Light Rare Earth Elements (Cerium)	Overproduction currently being landfilled	45 ppm	30–430
Light Rare Earth Elements (Europium)	>1%	2 ppm	
Light Rare Earth Elements (Gadolinium)	>1%	6.2 ppm	
Light Rare Earth Elements (Lanthanum)	>20%	35 ppm	12–230
Light Rare Earth Elements (Neodymium)	>1%	42 ppm	
Light Rare Earth Elements (Praseodymium)	>0.5%	9.2 ppm	
Light Rare Earth Elements (Samarium)	Overproduction currently being landfilled	7.1 ppm	

Lithium	>1%	30 ppm	4.6–100
Magnesium	Not suitable for magnesium production	2.1%	5000–110 000
Manganese	>30%	900 ppm	470–6800
Nickel - battery grade	>0.5%	80 ppm	11–400
Niobium	>0.2%	20 ppm	2.3–14
Phosphate rock	>2%	0.1%	170–23 000
Phosphorous	Not considered relevant		
Platinum Group Metals (Iridium)	>0.01 ppm	0.001 ppm	
Platinum Group Metals (Palladium)	>0.2 ppm	0.015 ppm	
Platinum Group Metals (Platinum)	>0.5 ppm	0.005 ppm	
Platinum Group Metals (Rhodium)	>50 ppb	0.001 ppm	
Platinum Group Metals (Ruthenium)	>10 ppm	0.001 ppm	
Scandium	>1000 ppm	25 ppm	3.9–42
Silicon	>90%	28%	
Strontium	>10%	350 ppm	29–1000
Tantalum	>100 ppm	2 ppm	0.18–28
Titanium	>10%	0.5%	700–7500
Tungsten	>500 ppm	1 ppm	0.59–897
Vanadium	>1%	150 ppm	26–550

Alum shale

Alum shale is a dark sedimentary rock that is finely layered with high organic content. Alum shale often contains high levels of sulphur together with both toxic and valuable elements, including uranium and CRMs like nickel, REE and vanadium.

Due to its problematic properties of swelling, acidic and toxic run-offs, and emissions of radioactive radon gas, alum shale is considered a problematic waste when run into during construction projects.

Indeed, road buildings and housing projects on alum shale-associated grounds often involve the removal of large amounts of this rock that must then be landfilled following complex and costly procedures. Both Sweden and Norway have large formations of alum shale, and several hundred thousand tonnes of alum shale waste is generated annually from construction projects.

On the other hand, alum shale has a long Nordic history as a raw material for producing various products such as dyes, pigments and metals. In some processes, alum shale is burned giving rise to an alum shale ash, sometimes called red pine, that is also landfilled at different Nordic sites in large amounts. Such ash has also been used in cement mortars as artificial pozzolans. Currently, this segment of use is covered by coal fly ash, but as coal-fired stations are closed in Europe, the need for replacement pozzolans will increase.

Compared to CRM-production from conventional ore, alum shale contains lower levels of relevant elements and must be disposed of at higher costs than conventional tailings. An interesting scenario, however, is the possibility of CRM-extraction as an integrated part of the disposal process. Such a process will also eliminate the environmental footprint from CRM, which the alum shale production process replaces. Landfilling of alum shales in Scandinavia carries costs of approximately NOK 1,000 per tonn, including documentation and transport costs.^[18]

Overall, hundreds of millions of tonnes of legacy alum shale are landfilled in the Nordics, including at least half a million tonnes of alum shale ash. Annually, approximately 250,000 tonnes of new alum shale are added to these landfills from ongoing construction projects. However, the total amount fluctuates significantly based on variations in activity levels that generate such waste. Due to the problematic properties of alum shale, these masses cannot be landfilled with other waste. Still, they must be transported to dedicated sites with strict and costly treatment procedures to avoid toxic leakage.

Nordic alum shale could potentially become a CRM-source if the treatment practice was adjusted to include an extraction process. The cost of such a recycling process will draw benefits from the fact that alum shale treatment is already associated with a high gate fee and without an income-generating product.

If a multi-metal processing plant for alum shale with an annual capacity of around 400,000 tonnes was built at a central Nordic location, this facility could potentially handle all Nordic alum shale waste, including volumes that today are handled by less-than-ideal clean-up operations that currently create unwanted local water pollution. Although the basic chemistry of alum shale treatment is straightforward, some technical challenges would have to be solved, including procedures for safely treating radon emissions. Relevant experience in dealing with these issues already exists in Nordic industries, for instance, the Terrafame and Sillamäe processing plants. The Swedish Geological Survey have also suggested alum shale processing as a direct response to the EU CRMA-initiative.^[19]

18. Personal communication with insiders in the roadbuilding and landfill industries in Norway.

19. www.sgu.se/en/mineral-resources/mines-and-environmental-impact/alum-shale/

There have also been several historic projects in Sweden^[20] and Norway^[21] that have developed industrial processes for the treatment of alum shale that, for different reasons, were never completed.^[22] Several technologies for CRM-extraction from alum shale have also been tested including REE^[23] and vanadium.^[24]

Bench tests have indicated that Swedish alum shales may be a relevant feedstock for vanadium, nickel and possibly also beryllium and rare earths.^[25] Experiences from an alum shale extraction facility in Estonia indicate that central CRMs can be extracted at efficiencies of around 70–85%.^[26]

Table 2.3 shows the range of CRM-concentrations found in Swedish alum shale and alum shale ash compared to the estimated minimum CRM-concentration in the waste stream for profitable and environmentally sustainable recycling. The table also includes typical background concentrations at which the CRMs are found in the earth's crust.

Table 2.3 Range of CRM-concentrations found in alum shale and red pine compared to estimated minimum CRM-concentration in waste stream for profitable and environmentally sustainable recycling. Data source: Sveriges geologiska undersökning.

Critical raw materials	Minimum concentration for recycling	Background concentration in the earth's crust	Alum shale/red pine (ppm)
Antimony	>1%	0.2 ppm	1.2–3.43
Arsenic	>10%	1.8 ppm	
Aluminum	> 50% alumina	8.2%	
Baryte	>10%	425 ppm	
Beryllium	>10%	3 ppm	3.2–6.5
Bismuth	>1%	0.2 ppm	0.06–0.23
Boron	>10%	10 ppm	
Cobalt	>0.2%	25 ppm	33–51
Coking coal	Not considered relevant	NCR	

20. Voronin et al. Chemical weathering of lower paleozoic black shales of south Sweden. J. of Mining Inst. 2018.

21. Abreham, A.Y. Reactivity of alum and black shale in the Oslo region, Norway. M.Th. Oslo University. 2007.

22. Freiberg, R. Rödifyr - En utredn. av användningsområden och hantering med fokus på ekonomi och miljö. Jönköping 2015.

23. Engström et al. REEs in the Swedish Alum Shale Form: A Study of Apatites in Fetsjön, Västerbotten. Uppsala University. 2019.

24. Gunnarson, N. The content, ch. state and acc. of V in a drill core of Alum shale from Kinnekulle. Diss. Lund University. 2019.

25. Jackson et al. Energy Independence for Europe: Uranium and Oil from the Alum Shale. 2010.

26. Maremaee et al. Metal extraction from alum shale ashes under the effect of ammonium sulphate. Oil Shale 1991.

Copper	>0.3%	68 ppm	147–224
Feldspar	>50%		
Fluorspar	>2%	590 ppm	
Gallium	>100 ppm	17 ppm	22–31
Germanium	>100 ppm	1.5 ppm	23–51
Graphite	>15%		
Hafnium	>2%	3 ppm	3.6–4.8
Helium			
Heavy Rare Earth Elements (Dysprosium)	>100 ppm	5.2 ppm	
Heavy Rare Earth Elements (Erbium)	>1%	3.5 ppm	
Heavy Rare Earth Elements (Holmium)	>0.5%	1.3 ppm	
Heavy Rare Earth Elements (Lutetium)	>50 ppm	0.8 ppm	
Heavy Rare Earth Elements (Terbium)	>50 ppm	1.2 ppm	
Heavy Rare Earth Elements (Thulium)	>10%	0.52 ppm	
Heavy Rare Earth Elements (Ytterbium)	>1%	3.2 ppm	
Heavy Rare Earth Elements (Yttrium)	>10%	30 ppm	
Light Rare Earth Elements (Cerium)	Overproduction currently being landfilled	45 ppm	230–300
Light Rare Earth Elements (Europium)	>1%	2 ppm	
Light Rare Earth Elements (Gadolinium)	>1%	6.2 ppm	

Light Rare Earth Elements (Lanthanum)	>20%	35 ppm	
Light Rare Earth Elements (Neodymium)	>1%	42 ppm	
Light Rare Earth Elements (Praseodymium)	>0.5%	9.2 ppm	
Light Rare Earth Elements (Samarium)	Overproduction currently being landfilled	7.1 ppm	
Lithium	>1%	30 ppm	15–56
Magnesium	Not suitable for magnesium production	2.1%	
Manganese	>30%	900 ppm	
Nickel - battery grade	>0.5%	80 ppm	147–230
Niobium	>0.2%	20 ppm	16–19
Phosphate rock	>2%	0.1%	600–1300
Phosphorous	Not considered relevant	NCR	
Platinum Group Metals (Iridium)	>0.01 ppm	0.001 ppm	
Platinum Group Metals (Palladium)	>0.2 ppm	0.015 ppm	
Platinum Group Metals (Platinum)	>0.5 ppm	0.005 ppm	
Platinum Group Metals (Rhodium)	>50 ppb	0.001 ppm	
Platinum Group Metals (Ruthenium)	>10 ppm	0.001 ppm	
Scandium	>1000 ppm	25 ppm	14–17
Silicon	>90%	28%	

Strontium	>10%	350 ppm	61–176
Tantalum	>100 ppm	2 ppm	0.9–1.4
Titanium	>10%	0.5%	5000–6000
Tungsten	>500 ppm	1 ppm	2–4
Vanadium	>1%	150 ppm	600–1400

2.2 Waste from processing raw materials

Jarosite sludge from zinc production

Mineral ores used for the primary production of zinc typically also contain several CRMs, such as germanium and gallium, although the composition varies widely between different ores. These CRMs are sometimes extracted as valuable byproducts together with zinc, but parts of the same CRMs will also be lost as waste.

One interesting waste stream from a CRM-recycling perspective that arises from the primary production of zinc is jarosite leach residue, which is an alkaline iron sulphate mineral. The CRMs that can be expected in this waste stream depend on the chemical characteristics of the ore and on the conditions of the hydrometallurgical process, through which it has been sent.

Two primary zinc refineries currently operate in the Nordics. This is the Boliden Odda plant in Norway and the Boliden Kokkola plant in Finland. Both plants are based on similar production technology and generate waste with comparable characteristics, due to their coordinated feed supply and management. Jarosite sludge is the dominating waste stream from both plants, where around 150,000 tonnes are generated annually in Odda and around 200,000 tonnes in Kokkola. The Odda plant is currently undergoing a NOK 5 billion upgrade – which will result in a doubling of both metal- and waste production.

However, none of these plants extracts the strategic metals germanium and gallium, or the associated non-CRM indium. As such, these plants and the millions of tons of aggregated wastes beside them are massive reservoirs of CRMs.

Together with the Finnish Research institution VTT Boliden has developed the Jarogain process for extracting some valuable materials from the jarosite.^[27] This process could potentially lead to a recovery process for CRMs,^[28] as well as reduced landfilling of waste. It is possible with matured technology to achieve high extraction rates.^{[29][30][31]}

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- 27. Kangas, P. The Jarogain Process for Metals Rec. from Jarosite and EAF Dust - Process Design and Economics. VTT. 2017.
 - 28. Rämä et al. Thermal Processing of Jarosite Leach Residue for a Safe Disposable Slag and Valuable Metals Rec. Metals. 2018.
 - 29. Karumb, E. The recovery of indium from mining wastes. M.Th. Colorado School of Mines.
 - 30. Swain et al. Recycling of Jarosite For Recovery of Valuable Metals and its Utilisation. IJSTRE. 2016.
 - 31. Ma et al. Stat. anal. and opt.of rec. In from jarosite res. with vacuum carboth. red. by response surf. meth. GP&S. 2016.

A successful implementation of a recycling operation for extraction of CRMs from the annual jarosite sludge production from Boliden could potentially cover all Nordic supply needs for germanium and gallium. If the millions of tonnes of jarosite from earlier production are reprocessed – all European needs could be covered as well. A competitor plant in Belgium is already looking into similar extraction.^[32] Also, work from outside of the Nordics indicates that jarosite residues might be the easiest way of reclaiming significant volumes of indium,^[33] although indium, for some reason, is no longer classified as a CRM.

When jarosite sludge is landfilled as waste in the caverns in Odda, it is sometimes mixed with other waste types including wastes from lead processing in Sweden. This may create obstacles to future CRM-recovery from the jarosite sludge. Because the jarosite sludge should be regarded as an important European CRM-resources, this waste stream should ideally not be mixed with other waste types without CRM-recycling potential, especially not hazardous wastes.

The establishment either of a modified flow sheet for the regular zinc production to extract minor CRMs early in the process or the building of a Jarogain-type of extraction will, in both cases, be an addition to an existing industrial infrastructure with all the benefits of access to competence, manning, energy, utility, logistics etc. The establishment of such units might also be expanded to include minor waste fractions from other industries or sorted materials from WEEE, such as germanium optic glasses or gallium diodes.

Surprisingly, the European Union has reached an agreement with Gecamines, a mining company in the Democratic Republic of Congo, to establish a plant dedicated to extracting germanium extracted from tailings for export to Europe. The first shipment of germanium from this plant was delivered in October 2024.^[34] Potentially, Norway and Finland should be equally significant suppliers.

Table 2.4 Typical concentrations (ppm) of CRMs and other raw materials of economic importance found in industrial jarosite sludge. Non-CRMs are marked with a *. Elements that should be considered for recycling are highlighted. Source: Bergfald Miljørådgivere.

	Min	Average	Median	Max
Aluminum	2,700	11,790	9,500	109,000
Antimony	5	1,035	800	4,000
Arsenic	100	3,496	3,187	10,414
Barium	25	5,231	6,053	17,600
Beryllium	0	0	0	0
Lead*	500	45,609	46,000	143,000

32. Rosendael et al. Selective rec. of In from iron-rich sol. using an Aliquat 336 iodide supp. ionic liquid phase (SILP). SPT. 2019.

33. Janošević, Miloš. Indium Recovery from Jarosite Pb–Ag Tailings Waste (Part 1). Minerals. 2023.

34. www.reuters.com/markets/commodities/congo-state-miner-gecamines-announces-first-germanium-exports-europe-2024-10-14/

Boron	0	0	0	0
Cerium	100	141	141	178
Dysprosium	0	0	0	0
Erbium	0	0	0	0
Europium	0	0	0	0
Fluorine	100	350	350	700
Phosphorous	3	473	501	1,200
Gadolinium	0	0	0	0
Gallium	40	307	310	1,500
Germanium	0	240	49	4,700
Gold*	0	15	15	50
Hafnium	1	1	1	1
Holmium	0	0	0	0
Indium*	10	283	239	850
Iridium	0	0	0	0
Copper	300	3,367	2,800	8,300
Cobalt	5	79	40	793
Lanthanum	4	29	29	100
Lithium	3	1,001	1,001	2,000
Lutetium	0	0	0	0
Magnesium	5	2,551	1,300	23,000
Manganese	100	20,025	4,100	337,000
Neodymium	1	3	3	5
Nickel	9	131	80	900

Niobium	0	0	0	0
Palladium	0	0	0	0
Platinum	0	0	0	0
Praseodymium	0	0	0	0
Rhenium*	0	0	0	0
Rhodium	90	90	90	90
Rubidium	66	76	76	89
Ruthenium	0	0	0	0
Samarium	0	0	0	0
Scandium	1	7	7	12
Zinc*	8,400	60,583	59,000	222,000
Strontium	146	850	709	1,650
Silver*	47	234	180	1,500
Tantalum	103	111	111	118
Terbium	0	0	0	0
Thulium	0	0	0	0
Tin*	62	7,544	4,100	105,916
Titanium	5	680	734	1,334
Vanadium	5	113	113	400
Bismuth	70	362	372	941
Tungsten	5	5	5	5
Ytterbium	21	24	24	26
Yttrium	178	202	202	226

Slag from steel production

Sweden, Finland and, to a lesser degree, Norway have a significant iron and steel industry that includes iron ore mines, blast furnaces, EAF steel and recycling furnaces, converters and processors, a broad fleet of alloy smelters and many foundries of varying sizes. The primary ore smelters of this industry generate large amounts of slag. Slag is typically formed when contaminants such as silica, sulphur and phosphorous are removed from melted metal by adding limestone and other materials. Aspiring to produce higher-purity iron will generally result in the generation of larger volumes of slag. Slags from most blast furnaces (BF) are dominated by the calcium from the added limestone, as well as the silica that follows most iron ores. In addition, there are several additional elements, including several CRMs that may originate from either the ore or the coke and other materials added to the process.

Most or all blast furnace slags are currently used as a substitute for cement, avoiding landfilling and providing a positive resource disposal and greenhouse gas footprint. However, when using the slag as cement, all CRMs locked in the slags are lost for recycling forever. One example could be residual levels of phosphorous and neodymium in iron ores from the north of Sweden, which are the remains of the apatite contamination left after flotation. While the flotation tailings with its REE content will be processed in the future, the remaining apatite minerals in the ore after flotation cannot. These CRMs will migrate to the slag and be locked into concrete forever.

The production of secondary iron and steel materials is based on Electric Arc Furnaces (EAF), which vary in size from annual capacities of one million tonnes down to much smaller plants for niche products. When using scrap metal, diverse contaminants are introduced into the furnace. Some come as alloying elements in the steel, and others from surface treatment (such as cadmiated^[35] or zinc steel components). Other origins of such contaminants are lead fittings, pigments in paints or lacquers or just because it is mechanically attached to the scrap iron components by glue, welding or screws. Magnets will sometimes also stick to ferric scrap metal and follow it into the recycling process. Indeed, slag analysis documents that several tens of tons of neodymium are currently lost in iron and steel slags in the Nordics.

When crude steel is made, it is mainly refined in a ladle. All of these processes, primary iron and steel, secondary iron and steel and ladle refining, produce slags with different volumes and compositions. In addition, alloys are added to make the final product. Many of these alloys are also produced in the Nordics, such as ferrosilicon from Elkem and Finnfjord, ferromanganese and silicomanganese from Eramet and FerroGlobe, ferrochromium from Vargøen, etc.

The disposal of the slags depends on its composition.^{[36][37]} While use as clinker replacement is financially attractive, it requires the slag to have sufficiently low levels of sodium, potassium, magnesium and manganese. Slag that is off-spec is used as aggregate,^[38] in agriculture^[39] or landfilled. For example, Höganäs in Sweden has developed a fertiliser product^[40] from their steel slag, and in the future, it might be a CRM-source.

Vanadium is a CRM that can be extracted from slags from the Swedish and Finnish iron and steel industries. The iron ores supplied by, amongst others, LKAB in northern Sweden have a naturally high vanadium content. In blast furnaces, this vanadium tends to be enriched in the slag and not

35. Cadmiated means treated with cadmium which is a hazardous heavy metal.

36. Engström, F. Mineralogical Influence on Leaching Behaviour of Steelmaking Slags. Luleå Uni. PhD thesis 2010

37. Mäkelä et al. Ev. of trace element avail. from sec. met. slag gen. in steelmaking by seq. chem. extr. Int. J. Env. Sci. Tech. 2013.

38. Lidelöw et al. Evaluation of leaching from four recycled materials used in full-scale road constructions.

39. Reijonen, I. Chem. bioavail. of Cr and V species in soil: risk ass. of the use of steel industry slags as liming mat. Diss. 2017.

40. Galyas, Eva. Ass. the suitability of using the byproduct Petrit-E from steel prod. as agric. fertilizer. MTh. Halmstad U. 2021.

in the iron. Vanadium is a scarce and valuable CRM, with 100% of the global production coming from BRICS countries, according to the latest USGS intelligence report,^[41] it is of particular importance to establish new supply lines.

The Nordics have a vast opportunity with the enriched slags coming from these ores. Substantial effort has, however, been put into extracting and utilising this resource more efficiently.^[42] Several thousand tonnes of vanadium might be recovered if a vanadium extracting/refining plant is built in the Nordics.

Reprocessing of slag from the iron and steel industry might also be a source of other CRMs. A detailed mapping of CRM-levels and other relevant chemical properties in individual slags from different plants would be required to improve the understanding of whether it can establish increased CRM-recycling.

On the other hand, it is important to observe that the global and Nordic steel industry is about to experience a transformational change by retiring traditional blast furnace plants (BF) and introducing direct reduction plants (DRI). While BF plants enrich most of the contaminants in the slag, the DRI plants do not. DRI technology is based on energy-efficient processes requiring higher-grade iron ores and with few contaminants. Contaminants in the ore will follow the pig iron to the steel ladle or EAF.

There are multiple effects of the technology shift from BF to DRI. The cement industry will no longer get BF slag as a clinker replacement. Pig iron production will focus more on high-grade processed magnetite and less on imported hematite.

Tailings production will increase. These refining requirements will simultaneously make it possible to extract CRM-rich feedstocks before pig iron production, making concentrates instead of slags.

EAF-dust from iron and steel recycling

When scrap iron and steel are used to produce secondary materials, they also bring additional elements into the process, either as alloy components or from surface treatment. During the production process in an electric arc furnace (EAF), these elements will follow the new secondary material, end up in the slag or evaporate from the furnace and later condensate as dust that is collected and delivered as waste. This EAF-dust typically contains high levels of recoverable zinc (15–50%) but also many other elements, including CRMs.

Based on the evaluations of 100 different analyses of EAF dust, it appears that the complexity of EAF dust has increased in recent years. This is most likely attributed to increasing volumes of electronic components unintentionally dragged with iron and steel components to steel recycling plants. The broad range of elements increasingly present in EAF dust, in combination with the expectation of increased EAF production in Europe, mandates a more thorough look into this segment, preferably in cooperation with other European nations to increase volumes and recovery grades.

Due to its high levels of zinc, EAF dust is often recycled in a Waelz kiln together with other zinc-rich waste materials that may include sludges, dross and small batteries. In the kiln, the dust is again volatilised, which separates zinc from other elements like iron and manganese. The non-volatile metals, including many CRMs, are left in an EAF slag that immobilizes these components in a way that makes further recovery difficult. Although other recovery processes have been

41. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-vanadium.pdf>

42. Attah, M. V re. from steel conv. slag utilised as an oxygen carrier in oxygen carrier aided combustion. JoCl.Prod. 2021.

developed that may recover additional elements in addition to zinc, these technology options have so far attracted little commercial interest or attention from governmental authorities.

It could be mentioned that the EAF dust is often processed in the Waeltz kilns together with manganese-based alkaline batteries, as these batteries also contain much zinc. Unlike zinc, battery-grade manganese is classified as a CRM. By combining these batteries with the EAF dust, all the non-zinc content is lost in a glassified slag.

Bergfald estimates the annual Nordic production of EAF dust to be between 100,000–150,000 tonnes. Some of the EAF dust, especially from smaller foundries, is landfilled as hazardous waste, instead of being delivered to recycling. If all Nordic EAF dust was collected and sent to a high-quality recycling plant, not only zinc but significant amounts of CRMs could also potentially be recycled.

Geothermal brines

Iceland has a large fleet of geothermal energy plants from which approximately 150 million tons of brine is discharged to various recipients. Brine from different locations contains various concentrations of metals, including lithium and boron. The high temperature and pressure of the brine may ease how soluble CRMs can be individually precipitated into relevant concentrates.

Geothermal energy on the scale of Iceland is not established and perhaps not even relevant for the other Nordic countries.

There seems to be a global trend towards a dual purpose of geothermal plants; partly to provide weather-independent power/heat – and partly to produce minerals. Large units for lithium extractions from geothermal plants are known from California and are currently planned in Germany. Today, Iceland produces precipitated silica (not a CRM as such), providing infrastructure and processing competence of immense value if a commercial CRM project is possible to develop.

The dual purpose of geothermal plants should be investigated further. It is proven that the deeper resources in Iceland have a much higher content of both base metals and even refractory metals.^[43] Concentrations in liquids might typically be 100–1,000 times in resources below 1,000 meters compared to shallow areas. Indeed, it is possible to envision deep geological mineral extraction plants in Iceland with a power byproduct, instead of shallow geological power plants with mineral byproducts.

Dross, slag and dust from primary and secondary aluminium production

All primary aluminium today is based on bauxite as a raw material, and many bauxite resources also contain CRMs, including gallium, germanium, scandium and REE. Global gallium production is, for instance, entirely based on recovery from upstream aluminium processing plants. However, almost none of the CRMs contained in bauxite are extracted. Most will end up landfilled in red mud, while the remainder will follow the aluminium oxide feedstock to the primary aluminium smelters in Norway, Sweden and Iceland, where they either dissipate into aluminium metal as a contaminant (most aluminium sold from the Nordics have a 99.5% purity) or end up in wastes from the smelters. During the primary production of aluminium, both liquid slag and solid dross are formed and removed from the process as waste. Better recycling of these waste streams could potentially recover more CRMs.

43. Saby et al. The behaviour of metals in deep fluids of NE Iceland. Nature. 2022.

Most aluminium in use is alloyed, and some of these alloy components are also CRMs, such as magnesium, titanium, scandium and REEs. Scrap aluminium usually contains significant amounts of other chemical elements which require treatment. Aluminium from shredded cars will, for instance, often have components of iron and copper beaten into it. Discarded beer cans often come with cigarette butts and are coated with pigment lacquers. When aluminium becomes scrap and is collected, sorted and sent to a secondary smelter, both the original contaminants and the alloying elements will, to some degree, end up in the dross from the secondary smelters. Salt is added to the recycling furnace, often potassium chloride, to bring some of the contaminants out of the melt, and quite often is, primary aluminium, added to dilute the contaminants. Monitoring the material flow and contaminant levels is key to success in aluminium recycling. This dross comes during the melting and is made by a mix of salts and oxides that are generated on the top of the melt and are regularly scraped off during the processing. Dross from secondary aluminium production is very different from dross from primary smelters, as it is less in volume due to little loss of aluminium oxide but is rich in many CRMs.^{[44][45][46][47][48][49][50]} Recycling process of CRMs from these waste streams is possible but comes with significant technical challenges that must be overcome to make this recycling a reality.

The best way to reduce the loss of alloying CRMs from aluminium is to stimulate and organise the specific sorting of alloys. Indeed, closing the material circle allows a worn-out aluminium component to be recycled for the same application. All aluminium scrap collected that is not targeted for specific alloy recycling will, for all practical purposes, result in some level of CRM-loss either by dissipation or loss to the dross.

Current processing capacities in the Nordics for aluminium dross focus entirely on aluminium. Metallic aluminium (droplets and small lumps) is recovered and returned to the primary smelters. The remaining material is regarded as aluminium oxide, although only 50% of the material is aluminium oxide. In any case, it is oxidised in a controlled manner, salts are washed out and pumped to the sea, and the rest is sold as aluminium oxide for clinker production.

When considering the size of the Nordic aluminium industry and levels of gallium in dross above 100 ppm, as well as several other relevant CRMs, it is important to consider if the waste mandates more advanced processing.

Spent pot liner (SPL) from aluminium production

Spent Pot Liner (SPL) arises as a waste from the primary production of aluminium when spent electrolysis baths are discarded and replaced in a volume of about 20 kg per ton of primary aluminium. The wall of the electrolysis bath is covered with a thick graphite cladding that isolates the bath from the refractory bricks in the wall behind the cladding and serves as a cathode in the electrolysis. During the aluminium production process, the graphite cladding gradually becomes saturated with fluorine and metals that do not evaporate or dissolve in the aluminium metal. Recycling of SPL can, therefore, lead to recovery of both fluorine and graphite and potentially other CRMs.^[51]

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- 44. Lucheva et al. Non-waste Aluminium Dross Recycling. J. of the University of Chemical Technology and Metallurgy. 2005.
 - 45. Afolabi et al. Compr. strength behaviours of lagoon-water cured cement-aluminium dross concrete. Kufa J. of Eng. 2021
 - 46. Sedo, Jan. Processing method and dross dust fractions properties in the Confal Inc. European Scientific Journal May. 2015
 - 47. Yang et al. Investigation of leaching kinetics of alu. extraction from sec. Alu. dross with use of HCl. Hydrometallurgy. 2019.
 - 48. Singh et al. Quantitative determination of metals in waste aluminium dross. IOSR JAC. 2018.
 - 49. Lin et al. Recycling of aluminium dross for producing calcinated alumina by microwave plasma. Sust. Env. Research. 2022.
 - 50. Wan et al. Synthesis of Cryolite (Na₃AlF₆) from Sec. Al. Dross Generated in the Al. Recycling Process. Materials. 2020.
 - 51. https://www.bergfald.no/wp-content/uploads/2019/06/Mindre-deponering-av-farlig-avfall_1.9_web.pdf

Due to the content of fluorine and cyanide, the SPL is a hazardous and difficult waste stream to handle that requires technically demanding and costly disposal solutions. But even recycling is challenging due to the toxic and chemically reactive nature of the waste material.^{[52][53]} Several companies are working on technologies to process SPL, and pilot plants are under construction, even in Norway.^[54]

Although some recycling of SPL takes place globally, all the Nordic SPL is landfilled, and no current recycling operation has recovered fluorine from SPL so far due to the technical challenges, although the fluorine concentrations in SPL are relatively high.

The challenge of SPL disposal is global, and the landfilling options are getting fewer and costlier. If a suitable recycling solution is developed and built in the Nordics, it is fair to expect that there will be a push from producers outside of the Nordics to supply feedstock at a reasonable gate fee.

Pyrite ash

Burning pyrite (iron sulphide) provides both processing heat and sulphuric acid. The remaining ash is an iron oxide, but often with a high content of other metals. Sometimes, pyrite resources are influenced by copper-containing chalcopyrite or other transition metal sulphides.^[55] Previously, there were many mines and sulphuric acid plants based on pyrite operational in the Nordics, however, there is only one left currently. Plans have been announced to establish one other. The amount of pyrite ash, the content of CRMs in the ash and the probable development of the sector do not mandate a significant regulatory effort.

2.3 Waste from discarded components, assembled products and decommissioned infrastructure and waste treatment

PCBs

Printed Circuit Boards (PCBs) are boards of non-conductive materials where conductive lines printed or etched onto the surface connect electronic components mounted on the board. These components often contain CRMs, and countless electrical and electronic products contain PCBs that can be collected during disassembly of the discarded EEE- products. PCBs come in all sizes, from massive server boards to tiny sensor components. Composition is likewise highly diverse, while valuable metals such as gold and copper are common for all PCBs.

In addition to the PCBs being highly diverse and heterogeneous, it is challenging to estimate the tonnage put on the market, the tonnage in use or storage and even the tonnage received and sorted for recycling. Recent numbers from Eurostat indicate a sharp increase in the sale of electronics all over Europe,^[56] and a higher growth in sales than in waste collection. Another source from the EU estimates that 400,000 tonnes of PCBs are placed on the market annually (2021).^[57] A third source indicates that the annual global demand for the composite resin used for

52. Ghazizade et al. Landfilling of prod. SPL in alu. Ind.: proposed method in dev. countries. 1st Int. C. on Final Sinks. 2010.

53. Kristensen et al. Mindre deponering av farlig avfall. Bergfald Miljørådgivere. 2019.

54. <https://www.eydecluster.com/no/aktuelt/2024/refacture-starter-urban-mining/>

55. Oliveira et al. Chemical comp. and minerals in pyrite ash of an abandoned sulphuric acid production plant. ACP. 2015.

56. [www.ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment)

57. <https://cordis.europa.eu/>

the circuit boards is 1.76 million tonnes.^[58] These different sources indicate a total production and inflow of PCBs in all sectors (both WEEE directive regulated and outside) of well above 400,000 tonnes in the EU. Indeed, it is possible that in the Nordic countries, almost 50,000 tonnes of PCBs are placed on the market annually, of which only about 50% is returned to a WEEE scheme later. The remaining PCBs are partly accumulated and partly lost in MSWI and shredder facilities.

It should be noted that not all PCBs are removed from the recycling plants for dedicated treatment. Small items are often lost, and items inside welded or glued chassis are often sent directly to incineration without sorting.

Most important for CRM-recovery, though, is the smelters. PCBs are sent to smelter hubs such as Boliden, Aurubis, and Umicore, with plants located in Sweden, Finland, Norway, and Europe. These smelter plants were initially built to process high-grade copper ores and have a long history and industry-leading metallurgical insight. Over a long time, these smelter hubs have developed new and advanced technologies to recycle lower-grade ores, increase recovery, decrease slag and emissions and introduce recycling of byproducts. Indeed, these plants now recycle gold, silver, and PGMs in addition to copper, as well as, to some degree, nickel and cobalt.

However, most of the CRMs in PCBs are not recycled when they are put into the copper furnace. Instead, it ends up in the slag^[59] from the smelters, and these slags that are often either landfilled, used for road building or as blasting sand.

Indeed, of the 70 elements commonly found in PCBs, 10 are recycled – while the rest are lost. Amongst the rest are 35 CRMs. The content of these non-recycled CRMs has increased over time, most notably in the last few years. While the recovery of the CRM copper has been improved over time, all the new CRMs coming into electronics have been largely ignored. The illustration below shows how the content of non-recycled CRMs in PCB has now passed 7% of total weight. This means that even if half of the PCB put on the market is returned to recycling, less than 50% of the copper used for electronics is recovered and 0% of the CRMs shown in figure 2.3.

58. www.chemanalyst.com/industry-report/flame-retardant-resin-in-ee-composite-market-677

59. Andertun et al. Long-Term Leaching Effects on CaO-Modified Iron Silicate Slag. Minerals. 2022.

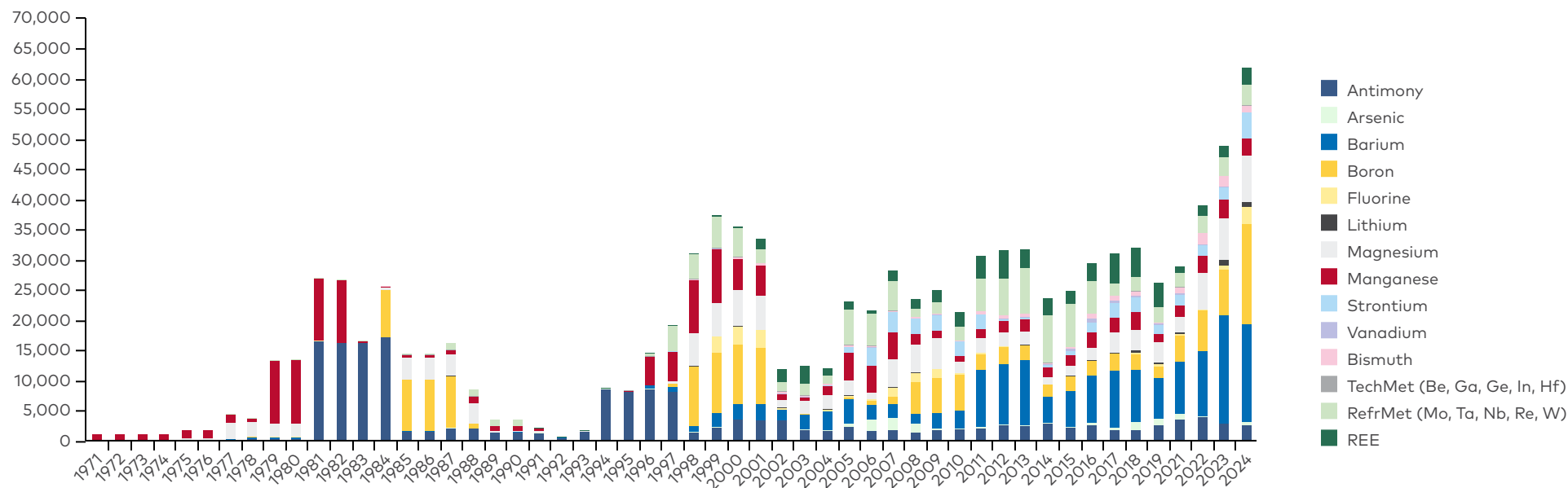


Figure 2.3 CRMs lost in PCBs, ppm. Source: Bergfald Miljørådgivere.

Both sorting and recycling operations focus on gold and copper and have yet to pay similar attention to the many other CRMs that PCBs contain. This has resulted in a recycling process that recovers less than a quarter of CRMs found in PCBs.

In addition, the collection system suffers from low collection rates for smaller products often lost or landfilled in incineration. Some sectors are also exempt from the EPR-schemes that secure collection and recycling for most WEEE, like the aviation, shipping, railway and military sectors and space programs.

It should also be pointed out that PCBs in cars and other road vehicles are not regulated by the same EPR schemes as other PCBs, which might increase the losses.

Cables

Cables are either a single wire or an assembly of wires used as a conductor to carry an electric current that delivers electric energy or a signal to the receiving component. Cables are often covered by an insulating and protecting material, typically a polymer. Cables come in countless dimensions and connections and are frequently laid out over long distances, sometimes dug down or built into the walls and foundations of buildings and infrastructure from where it can be challenging to recover. While copper is commonly regarded as the most crucial cable material, aluminium is a strong contender – when considering the HV grid going across all Nordics.

Cables such as copper and high-grade aluminium are significant consumers of CRMs. Globally, the total market for cables and wires is estimated at 25 million tonnes (all segments, both Al and Cu cables), giving an annual consumption in the Nordic market of approximately 440,000 tonnes. A third of this tonnage is polymers. At least half of the tonnage is also expected to be placed in infrastructure that is later decommissioned without returning to a recoverable waste stream. This includes copper wires from abandoned rail lines, copper wiring in houses not removed during demolition, cables dug down in urban infrastructures etc. Although temporally unavailable for recycling, cable materials left in urban infrastructure remain available for urban mining at a later stage.

It is estimated that half of what is put on the market is also returned to a recoverable waste stream. This indicates a substantial accumulation of metals in society, both material in use and out of use, as well as abandoned.

Some cables reaching a waste processing plant are recovered by some of the dedicated cable shredders (LINK), while some are lost in other shredder waste from cars and WEEE. As seen from shredder waste, copper and other metals levels are high.

As the circular economy grows, copper will face the same problem that currently is growing in the steel and aluminium sectors; the many alloys and contaminants that recycled copper brings with it may complicate or even poison the next generation of recycled metal.^[60]

The Nordic countries have a strong cable industry, with companies such as Nexans and NKT operating large plants for different dimensions.

Motors and generators

Electric motors convert electric energy to mechanical work through interaction between current-carrying conductors and a magnetic field. The exact process reversed is the basis for electric generators like dynamos and turbines, and some motors can also serve as generators, as seen in electric cars. Due to this duality, both motors and generators have quite similar designs and contain similar materials, including CRMs like copper and REE.

Electric motors are found in countless electric products that differ in size, from large propulsion systems, pumps, compressors and machines to small household appliances like electric toothbrushes and tools.

Efficient electrical motors based on the strategic and critical raw material neodymium have been crucial for developing modern electric engines and generators. These more efficient motors and

60. Loibl et al. Current challenges in copper recycling: aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America. *Resources, Conservation & Recycling*. 2021.

generators have made it possible to replace vehicles based on internal combustion engines with electric vehicles and increase the efficiency of electric components from the smallest sensor to the biggest windmill.

The most important CRM-component of electric motors and generators is the magnet for creating the magnetic field. Typical CRMs in such magnets include rare earth metals like neodymium, praseodymium and dysprosium. Other elements relevant to advanced magnets are boron, samarium, nickel and cobalt.

Currently, Europe has a recycling capacity for unutilised neodymium from scrapped magnets. This is due to bottlenecks in the collection and sorting of magnets. A central topic for Nordic CRM-strategies should thus be how magnets can be efficiently collected for recycling. This is more complicated than intuitively imagined, as many of the magnets are quite small and will stick to steel infrastructure in a recycling and sorting plant. Developing steel-free infrastructure for WEEE and automotive recycling will be challenging, costly and take substantial time to implement. The alternative will require vast manual work, which is also expensive. Lastly, even if significant magnet sorting is developed and implemented, the post-consumer magnets will have diverse metallurgical compositions, requiring elemental separation to be efficient.

As the Nordic countries have strong positions both in the upstream processing of magnet metals (neodymium, nickel, etc.) and in the production of motors, pumps, engines, etc., there are possibilities of achieving large effects if some of the inherent challenges are overcome.

LED and screens

Diodes are essential components in many electric and electronic products. Almost all new light sources and illumination technology on the market are currently based on diodes, and nearly all these are based on a gallium platform. Similarly, screens are also increasingly based on diodes.

So far, no significant recycling of WEEE-gallium exists. The current gallium recycling industry is only processing industrial scrap, although several teams are active in looking at different^[61] mechanical,^[62] pyrometallurgical^[63] and hydrometallurgical^[64] paths towards some recovery of gallium and other CRMs from post-consumer diodes^[65] and lamps.^[66]

All crude gallium processing is currently in China. As the Nordic countries have large gallium resources in the waste fractions from the aluminium and zinc industry, industrial development has remarkable potential. If gallium processing from industrial byproducts is established, looking thoroughly at the targeted sorting of diodes from WEEE would also be relevant. Importing diodes from other European countries would be relevant in such a case. As the overall figures are substantial, such an industrial setup will make Europe self-supplied for all gallium requirements.

Touchscreens also contain indium. While not a CRM in Europe, it is regarded as CRM in most other regions of the world. Diodes also contain highly strategic heavy rare earths like terbium.

61. Rebello et al. Reciclagem de lampadas de led inserviveis: Panora atual e perspectivas futuras. 2020.

62. Nagy et al. Recycling of gallium from end-of-life light emitting diodes. Arch. Metall. Mater. 2017

63. Chen et al. Recovery of Gallium and Indium from Waste LEDs. J.of the Korean Inst. of Res. Recycling. 2020.

64. Wei et al. Opt. of extraction of valuable metals from waste LED via response surface method. Trans.N.M.Soc. China. 2023

65. Mir et al. A Review on Recycling of EOL LED for Metal Recovery. The Minerals, Metals & Materials Society. 2022.

66. Nikulski et al. The Potential and Limitations of Critical Raw Material Recycling: The Case of LED Lamps. Resources. 2021.

Batteries

Batteries are portable or stationary energy storage units that allow chemical energy to be converted to electricity. Batteries differ in size from units that power a large ship to units in small medical instruments like pacemakers. Batteries are already one of the largest consumers of many CRMs, and this sector also has one of the highest expected growths in the coming years. So far, however, the volumes of material from discarded batteries available for recycling are still relatively low due to the length of the battery product life.

Different battery types contain varying CRMs. Among the dominant battery technologies are secondary batteries based on lithium-ion and lead-acid chemistries. Secondary batteries, commonly referred to as rechargeable batteries, can be recharged and reused multiple times. These technologies are expected to maintain or increase their market position in the coming years. CRMs that can be recovered from batteries include antimony, cobalt, graphite, nickel, lithium, magnesium and manganese.

The lead-acid battery technology is well-developed, robust, and cost-effective, though, with limited energy efficiency. The collection rate is exceptionally high, occasionally exceeding 100%. This can be attributed to consumers clearing out old garages and storage spaces, which is a favourable development. The collected batteries are transported to the Boliden plant at Bergsöe, which specialises in battery recycling and efficiently recovers battery materials.^[67] A minor fraction of slag and crust is removed during the process and subsequently disposed of in the Boliden Odda mountain cavern in Norway.^[68] The material composition of lead-acid batteries fluctuates over time, particularly concerning elements such as antimony and bismuth used in lead alloys. While most lead-acid batteries are utilised in mobile applications such as car starter batteries, there are also niche markets for stationary applications, such as power banks for solar panels in off-grid cabins.

Alkaline batteries are a type of primary battery designed for single-use applications and are widely utilised in everyday devices such as flashlights, smoke detectors, and toys. Historically, alkaline batteries have been based on a range of chemical compositions. In recent years, zinc and manganese have dominated the platform, with manganese being the only one currently considered a CRM. Due to their small size, the collection rate for these batteries remains relatively low. According to Eurostat, the collection rate for the category "Portable Batteries" within the Nordic region varies significantly, from 47% in Sweden to 77% in Iceland.

Portable batteries are sorted manually at the EPR plants in the Nordic countries. Alkaline batteries are sent to recycling plants outside of the Nordics for zinc recovery, which is not a CRM. The batteries are mixed with other zinc waste and fossil coke in these recycling plants and roasted. Approximately 80–90% zinc is recovered, while the battery-grade manganese is lost in a slag unsuitable for further processing. In all statistics, these tonnages of collected and sorted wastes with a CRM content of approximately 25% are registered as recycled. However, in reality, the CRM content has been entirely lost. Alkaline batteries, therefore, represent a significant opportunity to develop advanced recycling technologies that enable the recovery of manganese and other minor CRMs. Regardless of zinc not being classified as a CRM, it is still a substantial metal, and should not be overlooked by new recycling technologies.

Portable secondary batteries based on Nickel-Cadmium (NiCd) or Nickel-metal-hydride^[69] (NiMH)

67. <https://www.boliden.com/operations/smelters/boliden-bergsOE/>

68. <https://www.boliden.com/operations/smelters/boliden-odda/>

69. Shin et al. Recovery of el. Powder from spent NiMH batteries. Arch.of Met. and Materials. 2015

are typically used in power tools. However, lithium-ion batteries have increasingly dominated this sector in recent years. Despite the shift, significant legacy volumes of Ni-based batteries continue to enter and are expected to do so for several years.

A lithium-ion battery (LIB) generates electric current by migrating lithium-ion from one electrode to the other. Lithium is the lightest metal with the highest electrochemical potential, which makes it an excellent charge carrier. However, lithium constitutes only a part of the battery – about 2–3% or 8–12 kg in an EV battery weighing 400–500 kg. Typically, the anode is made of graphite, while the more complex structure of cathodes contains transition metals such as nickel, manganese and cobalt. These, along with other crucial components like the electrolyte and separators, are enclosed in a casing often made of aluminium.

There have been extensive plans to develop value chains for lithium batteries in Scandinavia, with companies such as Freyr, Northvolt, and Morrow, among others, taking the lead. However, they have faced unforeseen challenges, leading to an uncertain future for their production.

However, important industrial investments in both the reuse, refurbishing and recycling of used lithium batteries have been made in the Nordics. While the incoming volumes are not yet at a scale that can be described as industrial production, the sector is developing in that direction.

Scrapped vehicles

Vehicles contain many CRMs, often in large amounts, and scrapped cars are, therefore, a vital waste stream for CRM-recycling. Aluminium and magnesium are commonly used as construction materials, and components in steel are often alloyed with CRMs like nickel, vanadium and niobium. Some CRMs are already recycled quite effectively, like aluminium and copper. Vehicles also come with increasing numbers of electrical and electronic components typically containing gallium, germanium, silicon and REE in addition to copper.

When a vehicle is scrapped, it is typically stripped for oils, lead batteries and other hazardous materials before the remaining structure is crushed and shredded into manageable pieces. These pieces can then be sorted into limited metal fractions and delivered for recycling. Typical separation processes include magnetic separation of iron and magnetic steel, along with a combination of Eddy current separation, hand sorting, flotation and or sieving to separate non-magnetic metals like aluminium and copper. Some shredder plants have also developed solutions for separating specific alloys, although significant work remains to achieve a fully alloy-specific separation system.

So far, shredder plants where most vehicles end up are mainly built to recover the three primary metals: iron, aluminium and copper. Legislations, permits, and technological recycling concepts are all geared towards this. However, the metals coming out of these shredder plants are far from homogenous, often containing 5–10% of other metals. A German report from 2020 exposed that the iron fraction from shredding used cars only contained 92% iron. The rest were other metals, like aluminium, zinc and several CRMs.^[70] When this material is sent to the EAFs, it is regarded as 100% recycling. However, some iron goes into the recycling slag and some into alloying elements when remelted. Indeed, when considering the steel coming out of the EAF plants compared to the feedstock going in – the actual recycling rate is closer to 85–90%. Aluminium and copper encounter the same issue – the primary metal represents 90–95% of the fraction, while the rest comprises other metals. Both alloying elements, contaminants and base metals are lost in the process. When metal from shredder plants arrives at recycling plants, such

70. Sander et al. Evaluierung und Fortschreibung der Methodik zur Ermittlung der Altfahrzeugverwertungsquoten durch Schredderversuche unter der EG-Altfahrzeugrichtlinie 2000/53/EG. Umweltbundesamt, 2020.

as EAFs, or secondary aluminium smelters, it is crucial to monitor and compensate for these contaminants. Additionally, the increased recycling of minor CRM components could be achieved by optimisation of the recycling processes.

Some metals following the iron, such as chromium and nickel, will mainly remain in the steel and provide minor benefits. However, there are some challenges regarding other metals. For instance, a considerable amount of manganese is lost with the waste slag and evaporation. Zinc will also evaporate from the furnace, then cool down and precipitate in the EAF dust, where it subsequently can be recovered. In contrast, copper mainly remains in the iron, which is challenging for the steel industry.^[71]

Steel scrap currently contains approximately 0.2–0.5% copper, and increasingly, steel is becoming one of the largest sinks for this CRM. The losses of copper into steel alone represent volumes comparable to the total production of 10–20 medium-sized copper mines globally. It is challenging to justify the establishment of new copper mines when recycling operations remain so crude and unsophisticated, allowing such losses.

Indeed, improved sorting at automotive recycling plants and other parts of the recycling infrastructure may not only be beneficial – it might be fundamental to keep the recycling of steel at a sensible level.

When copper first enters the recycled iron melt, it can only be extracted with substantial energy costs and losses of material. In fact, the industry handles this today by blending different scraps and diluting them with pig iron, as well as by systematic downcycling. Scrapped car steel is used for rebar and manhole covers, and only a limited amount is used in new cars. Increasing degrees of iron recycling are giving rise to unfeasible challenges requiring new and strict upstream separation.

For aluminium, the situation is even worse. The European aluminium association has stated that

“the main flaw in current recycling processes is the practice of shredding the car as a whole which results in a mix of alloys: dismantling aluminium components before the shredder could be a solution”^[72]

The problem has been apparent for some time. High-quality aluminium from extruded, rolled or wrought components has been mixed and used as feedstock for casting components, efficiently making casting alloys the wastebin and end station for aluminium. Certainly, a decade ago, the Norwegian Aluminium Industry expressed concerns about the casting alloys sector being filled up with scrap from automotive recycling.^[73]

Without large leaps in alloy sorting efficiencies, the aluminium sector will continue to practice the substantial blending of secondary aluminium with virgin material to achieve necessary quality standards. In contrast, large amounts of CRM alloy elements are lost in the downcycled products.

In secondary aluminium plants, treating the incoming scrap with various chemicals are common to remove as many contaminants as possible before casting. However, as most of the contaminant metals stay in the aluminium, there is currently a systematic downcycling of aluminium, which is unsustainable.

A significant consideration for both CRM recycling and the quality of iron, aluminium and copper recovered from shredding processes is whether mixing waste materials prior to sorting is optimal.

71. Daehn et al. How Will Copper Contamination Constrain Future Global Steel Recycling? Environ. Sci. Technol. 2017

72. <https://european-aluminium.eu/>

73. Modaresi et al. Component- and Alloy-Specific Modeling for Evaluating Alu. Recycling Strategies for Vehicles. JOM. 2014.

To improve the qualities of both the main fractions of iron and aluminium – and provide a better possibility for CRM-recycling, developing this industry in the direction of pre-shredder dismantling and sorting might be the only sensible way forward.

Discarded tyres

Discarded tyres generates a large, constant and relatively homogenous waste stream. While natural and synthetic rubber constitute the primary materials, tyres also have a high content of inorganic components. Some of this is the steel alloy fibres, but the rubber itself also has a high inorganic (metal) content. Some of these metals are intentionally used as additives to optimise tyre properties. Some of the metals are contaminants from processing, such as catalysts, and some are natural contaminants from the growing of Hevea^[74] and some metals are even absorbed by carbon black in the rubber from the environment.^[75]

The synthetic SBR part of the tyre is mostly produced with neodymium catalysts, efficiently dissipating about 1,000 tonnes of neodymium annually globally. As such, neodymium sufficient to build 1 million electric cars is lost into car tyres – globally. If this is possible, recovery from the rubber has yet to be decided.

National annual volumes of scrapped tyres in the Nordics are estimated at 70 kt for Norway, 90 kt for Sweden, 50 kt for Finland, 40 kt for Denmark and 5 kt for Iceland, based on conversations with tyre return schemes and recycling industry representatives. Although used tyres in the Nordic countries are reported in national waste statistics as fully recycled, CRMs in the tyres are not. Car tyres shredded and used as a filtering medium in landfills are classified as recycling, as does export to Turkey for use in clinker plants, even if all the metals and CRMs are lost. Certainly, the potential for better recycling efficiency should be obvious for both high-alloyed steel and CRMs. Indeed, projects are now maturing trying to implement cryo- or pyro-technologies for accurate material recycling of composition parts such as carbon black. If carbon black recycling is implemented, beneficial side effects will occur as these technologies also liberate steel fibres and other inorganic content. One project of particular interest may be the new plant of Svensk Dekkåtervinning, and the possible downstream processing by Rubber Innovation. This site might also be further developed to extract and recover some of the critical metals content. It could be that pyrolysis will open the path towards recycling much inorganic material of high value.^[76]

Policy options that should be considered for developing better CRM-recycling of discarded tyres include a ban on using spent tyres as infill and drainage layers at landfills and restrictions on exporting tyres out of the EU, including export to Turkey and Morocco. Technological development of neodymium-free CBR rubber production should also be incentivised.

Shredder residues

The shredder plants are the largest and most visual component of the Nordic recycling infrastructure. Large, metal-containing waste such as scrapped automobiles, production machines, cables, and poles have been collected, sorted and recycled due to inherent metal values for many years. As society takes in new metals and alloys, and environmental requirements have increased – so has the technological level of this infrastructure. Within the span of only one generation, this sector has developed from scrapyard to process industry.

74. Thepcalerm, C. Study of the mesostructured by AF4-MALS and of the mineral element comp. by ICP-MS. PhD Th. 2014.

75. Shahraki et al. High eff. Removal of heavy metals using tire-derived activated carbon vs commercial activated carbon: insights into the adsorption mech. Chemosphere. 2021.

76. Naveed et al. Gasification Characteristics of Auto Shredder Residue. J.Chem.Soc.Pak. 2011.

This industry is represented by several plants in Norway,^[77] Sweden,^{[78][79][80]} Denmark^{[81][82][83]} and Finland.^[84] Scrap cars and other metal-containing wastes are shipped from Iceland and the autonomous areas for shredding in mainly Sweden or Denmark. Historically, there has been quite a lot of trade of both un-shredded and partly processed scrap back and forth across the North Sea, complicating these statistics.

Although the scrap industry has been through significant development in the last three decades – it is still a volumes industry. The core fractions are iron, copper, aluminium, and burnable fluff. As the scrap delivered to these plants contains increasing levels of CRMs, this industry currently represents potentially the largest losses of Critical Raw Materials, and simultaneously, a sector with similar potential for CRM-recovery with limited efforts of costs.

Shredding of metallic waste creates two residual waste streams that are challenging to recycle. They are often referred to as fluff and fines. Fluff is the basket definition of all the nonmetals, such as polymers, textiles and rubber, that arise from shredding processes. The most common disposal of the fluff is incineration. Fines are as the word says, finer particles and dust created when cars are smashed to pieces, a mix of everything. Both fractions also contain residual levels of metal particles. Combined, the fluff and the fines are generally categorised as “shredder residues”, a material with limited market value but is required to be disposed of as waste. Notably, both the fluff and the fines contain all CRMs, and in large volumes. As cars and other equipment contain more and more advanced technologies, often as tiny sensors – the many small bits and pieces end up as a sizeable total loss.

Extensive work on mapping the loss of critical raw material has been done in cooperation between Swiss and Norwegian researchers concerning the CRM content in automotive shredder residues.^[85] Indeed, the mass balances produced indicate that the stock of the most critical CRM Neodymium in car electronics is higher than in all consumer electronics combined (computers, laptops, entertainment units, mobile phones, TVs, music systems etc.). As an example, the reported volumes of shredder residues and the average levels of CRMs indicate an annual loss of 112 tonnes of neodymium and 11 tonnes of dysprosium. That is a volume from which 100,000 fully electric cars could have been produced – if the CRMs had been fully recovered.

Post-shredding separation of these small components seems challenging and expensive, though possible. Potentially, a more resource- and cost-efficient solution could be implementing routines and regulations for pre-shredding dismantling of car electronics, including sensors. Introducing specific recycling mandates for these components equal to those applied for consumer electronics.^[86] Modern automobiles, whether ICEs or EVs, contain a lot of small motors, for instance, window wipers, window hoists, electronic locks, seat adjustments, and air fans. Each of these motors contains grams, and sometimes fractions of grams of CRMs. But as it is many of them, they aggregate to many tons.

Currently, cars and all other rolling equipment (such as trains, bikes and buses) are exempt from the WEEE regulations that almost all other sectors are mandated by. Hence, this feedstock is

77. Hovde, L.R. Analyser av lettfraksjon fra fragmenteringsverk. Hjellnes Consult. 2007.

78. Stanicic et al. Fate of lead, copper, zinc and antimony during chemical looping gasification of ASR. *Fuel*. 2021.

79. Faust et al. Interactions between ASR and Olivine BedMaterial during Indirect FB Gasification. *Energy&Fuels*. 2021

80. Jagodzinska et al. Can torrefaction be a suitable method of enhancing shredder fines recycling? *W. Management*. 2021.

81. Nedenskov et al. Shredder Waste and mixed waste, DHI Miljø. 2011.

82. Hjelmar et al. Treatment methods for waste to be landfilled. *TemaNord* 2009:583.

83. Boldrin et al. Life cycle assessment of shredder residue management. *Miljøstyrelsen*. 2015.

84. Nieminen et al. Gasification of shredder residue. *VTT*. 2006.

85. Restrepo et al. Stocks, Flows, and Distr. of Critical Metals in Embedded Electronics in Passenger Vehicles. *ES&T*. 2017.

86. Restrepo et al. Effects of car electronics penetration, integration and downsizing on their recycling potentials. *RC&R*. 2020.

currently lost in the shredder residues. Indeed, one of the lowest-hanging fruits for increased CRM-recovery before 2030 would be for automotive electronics to be included in the WEEE mandates or have similar recycling requirements as all other electronics in society.

The current recycling of electronics is not extracting the most critical CRMs, but substantial development work is ongoing to make that happen. Indeed, it is expected that technologies will mature, and recycling plants will be built and expanded in the years ahead.

Shredder residues will typically have two disposals in the Nordics; the fluff consisting of mainly plastic and rubber with small pieces of metal, will be burnt, either in MSWI plants or cement plants. The fines, consisting of high levels of metal particles partly diluted by hard plastic particles, are generally landfilled. Both fractions have high levels of CRMs, but the fines fraction is, of course, of the highest recycling and supply interest.

To some degree, the fluff fraction is also landfilled. The open-air disposal of finely ground metal particles together with fluffy plastic particles has been shown to result in uncontrolled fires regularly. Indeed, every summer there are fires on landfills with fluff, which spread both halogenated organic toxins and heavy metals into the environment.

One possible path for the Nordics would be to incinerate all fluff from Nordic shredders in one dedicated MSWI plant, to get a high-metal-ash suitable for hydrometallurgical downstream processing. This has been considered before,^[87] and is not without its issues, for instance, in handling the high halogens and inorganic content. On the other hand, the volumes of metals that potentially would come from such a plant could potentially be recycled and should mandate considering this option.

Critical perspectives that should be considered when framing policies for further development of the Nordic shredder industries include mandates of increased pre-shredder sorting that will create some additional costs and demand more manual labour, but at the same time will improve separation of individual metals and alloys and enable improved CRM-recycling. In addition, a ban on landfilling and incineration of shredder residues that contain recoverable levels of CRMs (>1%) should also be considered.

Ashes

Ashes are formed when combustible materials are incinerated. Incineration is often used as a waste treatment process that sanitises and stabilises the waste material and leaves residual matter requiring less landfilling. When energy from the incineration process is utilised for electricity production or heating purposes, waste incineration plants are also referred to as waste-to-energy plants. Most incineration processes create two main types of ash. Bottom ash is the largest fraction and is collected from the bottom of the incineration chamber. It consists of inorganic chemical compounds with low levels of organic matter. Fly ash is ash particles that follow the flue gasses and are collected as part of the flue gas treatment system. Compared to bottom ash, fly ash contains higher concentrations of volatile metals like arsenic, antimony, lithium and zinc. Ashes are similarly formed when biomass is incinerated to create heat for either industrial use or household heating. Ashes from incineration processes contain all the chemical elements of the periodic table at different concentrations.^[88] While the average grade of different CRMs is relatively consistent over time, there are huge differences between different ashes based

87. Johansson et al. Separate comb. of selected waste streams to increase resource recovery from ashes. Re:source. 2017.

88. Kalembkiewicz et al. The Physicochemical Prop. and Comp. of Biomass Ash and Ev. Dir. of its Appl. Pol. J. Env. Stud. 2018

on what materials are incinerated. Some ashes contain levels of CRMs similar to, and even higher than, commonly used primary ores, but more often, these levels are minor.

The Nordic countries generate around 6 million tonnes of ashes from incineration of waste and biomass. Some of the ashes are utilised as concrete replacement or fertiliser, while most are landfilled as either inert or hazardous waste. The levels of total CRMs in these ashes are averaging around 1%, even when excluding elements such as aluminium, magnesium and silicon - representing a substantial loss of CRMs and a combined volume that should not be ignored as a potential feedstock for future CRM-recycling. Despite large volumes and consistent supply, the CRM-extraction from ashes will be challenging.

The feedstocks for the biomass plants are also different.^[89] While all countries use different types of wood/forest-related feedstock, Finland has significant volumes of peat,^[90] while Denmark has significant volumes of straw. Some countries incinerate sludge from wastewater treatment; others use it as direct fertiliser. Sweden and Finland have huge forest industries with large CHP boilers for bark and residues. Denmark has former coal-fired power stations rebuilt to use domestic and imported biomass fuels.

MSWI ashes have historically been regarded as problematic and sometimes hazardous, which has created a need for safe disposal.^[91] Hundreds of projects globally have used bottom ash as filler material in building projects,^[92] and fly ash has been used as concrete addition, but only recently has the ash been seen as a possible feedstock of important metals.^[93]

While WEEE schemes worldwide, and in the Nordics, have increased and improved the collection rate, we still observe a high influx of WEEE-related material to the MSWI streams. While the larger components that WEEE systems were initially built for, like TV-sets and computers, have a high collection and sorting rate, we observe a multitude of minute WEEE components in the society that we expect to be discarded as MSW. Examples include parcel ID trackers, toys, gimmicks, air pods, memory sticks, credit cards, ID cards and pointers. These generally end up in the MSW, and later, the metals are found in the ash.

Toys are recently highlighted as a tsunami of WEEE waste.^[94] In just a few years, it has become common and inexpensive to put electronics in any toy sold. This year, it is estimated that 7.3 billion toys with WEEE materials inside are discarded. That is one toy for every living person on the globe. Even the most advanced WEEE sorting systems have problems with these toys, so we expect close to 100% loss of the contained metals from these items to end up in incineration ashes.

Due to limitations in oxygen during certain phases of the incineration process, there will also be reductive reactions in certain zones, despite the dominant net process being oxidative, leading to somewhat counterintuitive changes in metal components passing through the incineration process. For instance, aluminium components in MSWI plants absorb some CRM-metals during the incineration – ending up with a different alloy composition than what was fed in.

Bottom ash is normally post-treated by magnetic separation, sieving, and, most commonly, eddy-current separation to get out larger aluminium components, which, as expected, will lead to reduced levels of metallic components in later bottom ash analyses.

89. Dijen, F. Bioefficiency - Influence of pre-treatment, blending and additives on ash composition (D6.2). 2019.

90. Perämäki et al. Occ. and rec. pot. of REE in Finnish peat and biomass combustion fly ash. J. of Geochemical Expl. 2019

91. Holmstrøm, P. Aske som ressurs. Avfall Norge. 2012.

92. Maresca et al. Life Cycle Assessment of future management options for Danish MSWI fly ash. MST report. 2019.

93. Skåra, A.R. Gjenvinning av verdifulle grunnstoffer fra saltutvasket flyveaske. M.Th, University of Oslo. 2022.

94. weee-forum.org/ws_news/invisible-e-waste-almost-10-billion-in-essential-raw-materials-recoverable-in-worlds-annual-mountain-of-electronic-toys-cables-vapes-more/

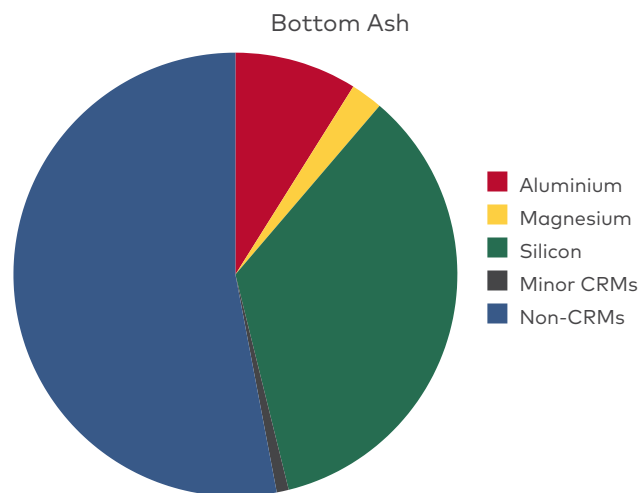


Figure 2.4 Relative levels of CRMs in bottom ash. Source: Bergfald Miljørådgivere.

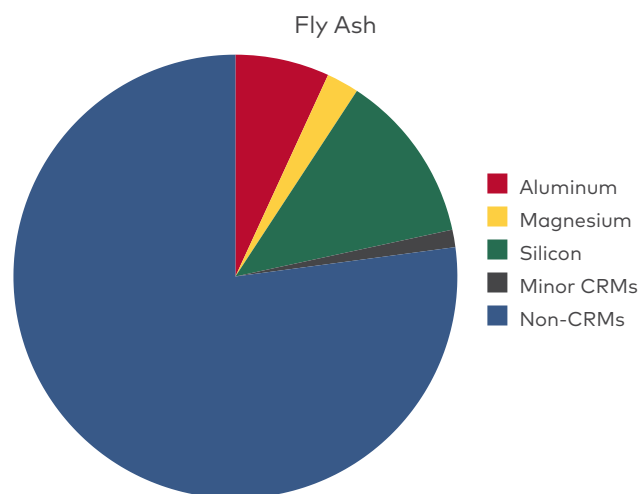


Figure 2.5 Relative levels of CRMs in fly ash. Source: Bergfald Miljørådgivere.

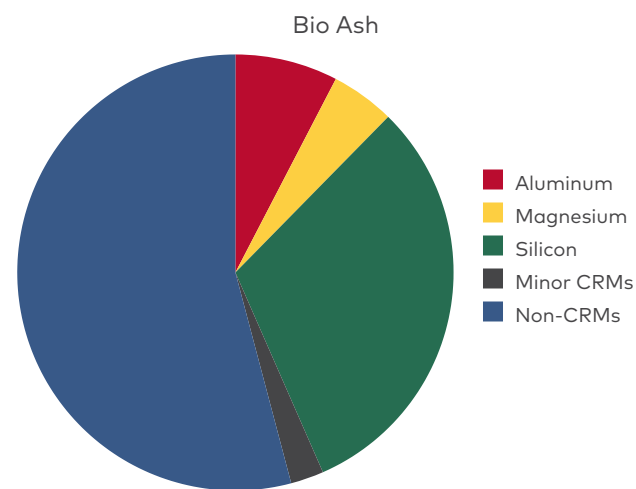


Figure 2.6 Content of CRMs and non-CRMs in different ashes. High value minor CRM levels of 1–2% is comparable to mined resources. Source: Bergfald Miljørådgivere.

Work has been conducted in Denmark to map REE and other CRMs in ashes from different sources, such as MSWI in Greenland^{[95][96]} and biomass in Denmark.^[97] Several Nordic initiatives actively try to extract valuable materials from ashes,^[98] or use the ashes as a substitute for other materials.^[99] It has been shown that it is possible to extract phosphorous, zinc,^[100] and copper^[101] from MSWIFA in Sweden. Many stakeholders are also working on extracting salts,^[102] mostly from MSWI fly ash.^[103]

The Finnish Forest Engineers Association estimates an annual production of 650,000 tons of bio ash in Finland.^[104] Ash from Finnish pulp industry is quite interesting as an industrial large bio ash resource,^[105] because it has a different composition than the other Nordic countries.^[106] This difference is probably due to a combination of use of peat and widespread geological resources of base metals. In Sweden, the Nordic Council estimates 800,000 tons,^[107] numbers that include several very different sources.

Organic waste

Phosphate is an essential chemical component of all living cells, and so all organic waste contains phosphate, albeit at low concentrations. When organic waste is allowed to undergo anaerobic digestion in a closed reactor, collectable bio-methane is formed that is chemically identical and can be used for the same purposes as natural gas. The biogas formation leaves a phosphate-enriched digestate sludge that can be used directly as biofertiliser or processed into a more concentrated and drier product. When used locally, the digestate can be applied as fertiliser without any further processing. However, the high-water content makes transport over longer distances both costly and energy intensive.

One way to concentrate the phosphate content is through the combustion of the digestate, which leaves dry phosphate-enriched ash where microplastic, organic pollutants, infectious agents and seeds from blacklisted plant species have been removed. Further refining phosphate from biogas production could potentially also replace phosphate rock in production of synthetic fertiliser.

There is already a well-developed biogas industry in the Nordics, especially in Denmark, Sweden and Finland, that could potentially be expanded further.

Another source of phosphate from organic waste comes from wastewater treatment. Phosphate is most often not removed during the treatment process, but there are available techniques for phosphate removal, for example, through struvite precipitation.

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- 95. Kirkelund et al. Greenlandic MSWIFA and MSWIBA as secondary resource in Mortar.: Int. J. Sus. Dev. Plann. 2016.
 - 96. Kirkelund, G. Ch. of MSWIBA for pot. use as a subbase in Greenlandic road construction. Tech. Uni. of Denmark. 2012.
 - 97. Lima et al. Screening dilute sources of rare earth elements for their circular recovery. J. of Geochemical Exploration. 2022.
 - 98. Seres, S. Resource recovery from MSW fly ash. M.Th. Umeå University. 2018.
 - 99. Hanson, L. Characterization of bottom ash from MSWI as a possible element in concrete. M.Th. Chalmers. 2017.
 - 100. Fedje et al. Zinc recovery from Waste-to-Energy fly ash – A pilot test study. Waste Management. 2020.
 - 101. Tang, J. Removal and Recovery of Metals from MSWI Ashes by a Hydrometallurgical Process. PhD.Th. Chalmers. 2017.
 - 102. Johansson, K. LCA of tr. proc. for FA from MSWI – A comp. of the Ash2Salt process and existing tr. meth. SLU. 2017.
 - 103. Nedkvitne et al. Variation in chemical composition of MSWI fly ash and dry scrubber residues. Waste Management. 2021.
 - 104. www.puunjaloostusinsinoorit.fi/en/about-pi/
 - 105. Oksanen et al. Fertiliser prop. of wastewater sludge and sludge ash—a case st. from the Finnish forest ind. E.Ch.EngS. 2023
 - 106. Pöykö et al. Heavy metals leaching in BA and FA fractions from ind.-scale BFB-boiler for ERA. Tr.NFe Met. Soc. China. 2016
 - 107. Nordic Council of Ministers. BAT for combustion and incineration residues in a Circular Economy.

3. Nordic companies and industrial projects that may lead or take part in new or better CRM-recycling operations

The Nordic fleet of base metals industries is an important platform for developing increased CRM recycling quickly. Setting up new secondary CRM-value chains from scratch has proved to be very difficult. It might be even worse in today's market situation with Asian market dominance and unpredictable price fluctuations. New industrial enterprises often need an economic edge to succeed, either in terms of cheap and readily available raw materials, comparatively low energy price or labour costs, superior technology or expertise and so on. It is, therefore, often easier for existing companies with comparable products, processes and an existing market position to branch out from than for a start-up company to succeed at such an endeavour. An industrial company can often use in-house expertise in their planning and design of the project, raise investment capital more efficiently, and obtain necessary governmental permits and offtake agreements^[108] for their secondary CRM-product with fewer risks. For this reason, when considering the potential for new Nordic secondary CRM-value chains, one should consider existing industrial operations as a potential starting point.

Sometimes it is also possible to use CRM-containing waste as additional feedstock in primary production processes, although contamination issues and technical considerations will often limit these options. In situations where CRM-containing waste streams can serve as additional feedstock in primary production processes, this may eliminate the need for additional infrastructure serving a secondary production process.

This chapter, therefore, highlights some existing Nordic industries or projects that could potentially have a role in creating new or strengthening existing secondary value chains.

3.1 The Nordic aluminium industry

Aluminium is a CRM in its own right, but many aluminium alloys also contain other CRMs like scandium, magnesium, manganese and silicon. Better recycling solutions in this sector may, therefore, reduce supply risks for these CRMs as well as for aluminium. In addition, the aluminium oxide used as feedstock for primary aluminium production contains the CRM gallium that may be extracted from waste streams leaving the electrolytic process. During both primary and secondary aluminium processing, some aluminium oxide escapes as waste from the process. This aluminium oxide is typically lost either when it is landfilled or downcycled as a raw material in clinker production in the cement industry.

¹⁰⁸ Off take agreements are long-term legal contracts where a buyer undertakes to buy the future production from a supplier. Off-take agreements are an important tool for reducing financial risk when establishing new production capacities.

With a more circular perspective on alloy design and collection and sorting of aluminium waste streams, more aluminium can potentially be recycled, and a larger portion of other CRM-alloy components can potentially obtain meaningful roles in future product lives instead of becoming a diluted pollutant or being lost in waste streams from the recycling operation. There are also R&D initiatives worldwide to develop technologies that eliminate the need for the CRMs fluorine as a chemical input in the electrolysis process and graphite for anodes and cathodes.

There is a large Nordic aluminium industry both when it comes to primary and secondary production capacity. In addition, there are also several refineries for more advanced aluminium products. Norway has the largest production capacity for primary aluminium with five plants operated by Hydro and two plants operated by Alcoa. Iceland has three primary production plants operated by Rio Tinto, Alcoa and Norðurál. Sweden has a large primary production plant in Sundsvall operated by Rusal.

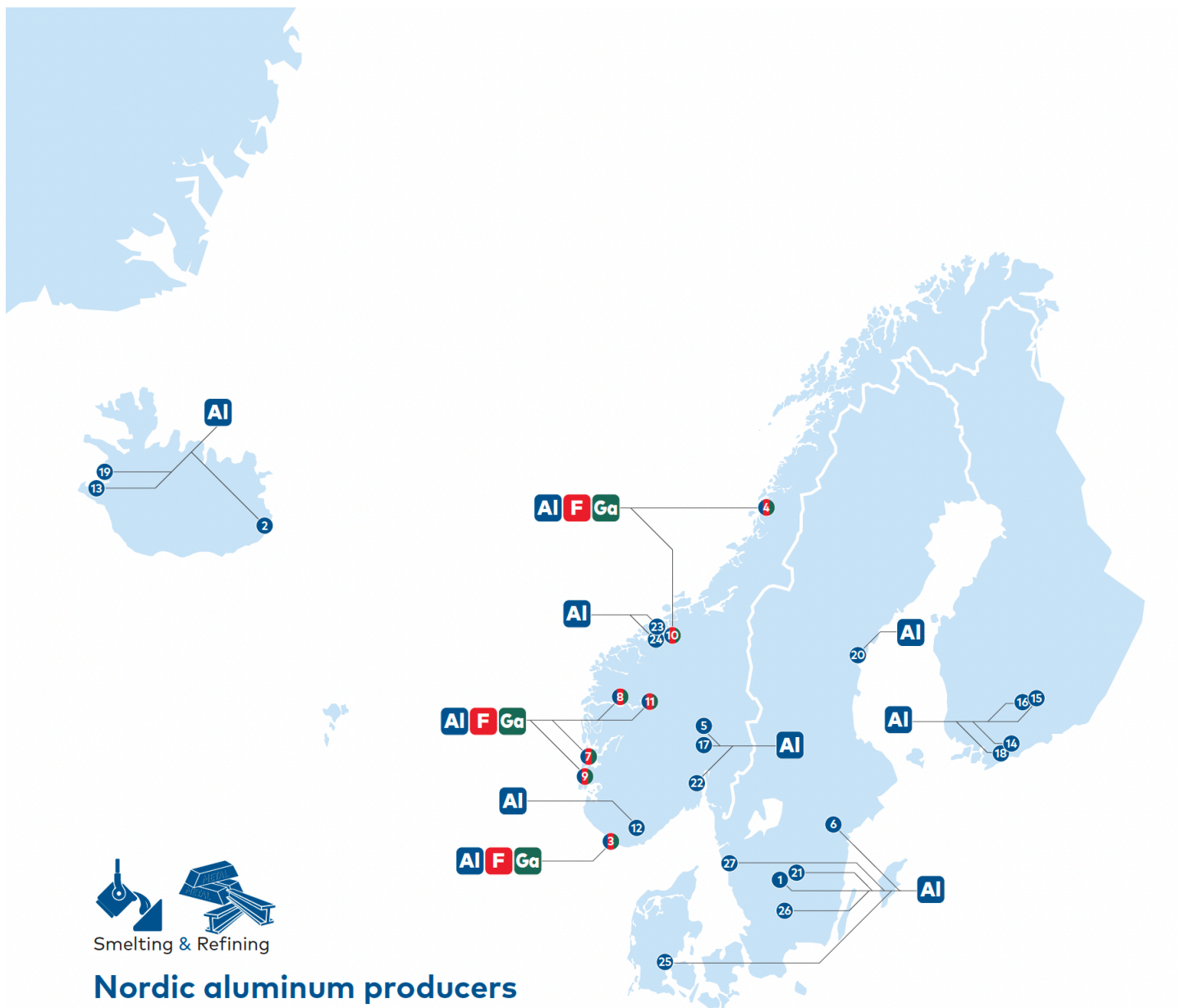
There are also many production plants for secondary aluminium in the Nordics. Most of these plants recycle a blended mix of aluminium alloys, which can lead to reduced material quality compared to primary aluminium, and also lose the utility value of much of other CRMs in the aluminium scrap used as feedstock. Better sorting of individual aluminium alloys and selective recycling of specific alloys in dedicated recycling plants could potentially reduce the CRM-loss at the end of the aluminium product life.

Norway also has a production plant for high-purity primary aluminium, the Vigeland plant. This plant refines high-grade primary aluminium from 99.7% to 99.99%, extracting typical contaminants such as iron, silicon and gallium. If feedstock for such production was changed from high-grade aluminium to 99.5% purity with high content of CRMs (such as primary aluminium from Alcoa with high gallium) or speciality alloy scrap with high CRM, the refining waste from this process might be relevant CRM-feedstocks. The competence in refining high and ultrahigh aluminium is, in any case, highly relevant to understanding possible circular value chain adaptations.

Recycling options to recover CRMs should be considered not only for aluminium scrap but also for relevant waste streams leaving the aluminium production processes. Speira operates two recycling plants for such waste in Norway. Several CRMs could potentially be recovered from these plants if additional extraction and refining units were added to the existing infrastructure.

There is also a potential for recycling waste fluorine from primary aluminium production through the aluminium fluoride production plant in Odda, currently owned by the Fluorsid group. Waste fluorine from the aluminium sector could potentially replace fluorspar imported from Morocco as feedstock to produce aluminium fluoride, although this will require some technical adjustments to the current process.

Figure 3.1 shows an overview of the Nordic aluminium industry. A detailed list of Nordic aluminium plants can be found in [Annex Table 2](#).



COMPANY	POTENTIAL CRM	PROCESS	COUNTRY
1. AB Lundbergs Pressgjuteri, Vrigstad	Al	Secondary smelter	Sweden
2. Alcoa Fjarðarálf	Al	Primary aluminium smelter	Iceland
3. Alcoa Lista	Al, F, Ga	Primary smelter	Norway
4. Alcoa Mosjøen	Al, F, Ga	Primary smelter	Norway
5. Benteler Aluminium Systems, Raufoss	Al	Foundry	Norway
6. Gränges Aluminium, Finspång	Al	Secondary smelter	Sweden
7. Hydro Aluminium, Husnes	Al, F, Ga	Primary smelter	Norway
8. Hydro Aluminium, Høyanger	Al, F, Ga	Primary smelter	Norway
9. Hydro Aluminium, Karmøy	Al, F, Ga	Primary smelter	Norway
10. Hydro Aluminium, Sunndal	Al, F, Ga	Primary smelter	Norway
11. Hydro Aluminium, Årdal Metallverk	Al, F, Ga	Primary smelter	Norway
12. Hydro Vigeland's Brug AS Vennesla	Al	Refinery	Norway
13. Isal (Rio Tinto) Hardarfjörður	Al	Secondary smelter	Iceland
14. Kuusakoski Oy, Espoo	Al	Secondary smelter	Finland

COMPANY	POTENTIAL CRM	PROCESS	COUNTRY
15. Kuusakoski Oy, Heinola	Al	Secondary smelter	Finland
16. Kuusakoski Oy, Myllyoja	Al	Secondary smelter	Finland
17. Mettaco aluminium AS, Vestre Toten	Al	Foundry/recycling	Norway
18. Nordic Aluminium Ltd, Kirkkonummi	Al	Secondary smelter	Finland
19. Century, Grundartangi	Al	Primary smelter	Iceland
20. Rusal i Kubal, Sundsvall	Al	Primary aluminium smelter	Sweden
21. Sapa (Hydro), Sjunnen	Al	Secondary smelter	Sweden
22. Speira, Holmestrand	Al	Secondary smelter	Norway
23. Speira, Rausand	Al	Recycling aluminium from slag and dross	Norway
24. Speira, Red	Al	Recycling aluminium from slag and dross	Norway
25. Stena Gotthard, Kolding	Al	Secondary smelter	Denmark
26. Stena Gotthard, Älmhult	Al	Secondary smelter	Sweden
27. Volvo, Torslanda	Al	Secondary smelter	Sweden

Figure 3.1 Overview of the Nordic aluminium industry. Illustration: Bergfald Miljørådgivere.

3.2 The Nordic zinc, copper and nickel industry

Zinc, copper and nickel are often found in overlapping ores, as illustrated in Figure 3.2, and are therefore often extracted and refined together in common industrial processes, sometimes with additional CRMs as byproducts. Because the same components are also commonly found in similar waste streams like batteries, WEEE and End-of-life - vehicles, secondary production of these CRMs together from a joint recycling operation may sometimes also be sensible. Both pyrometallurgical and hydrometallurgical technologies are used for recovering these CRMs from waste streams.

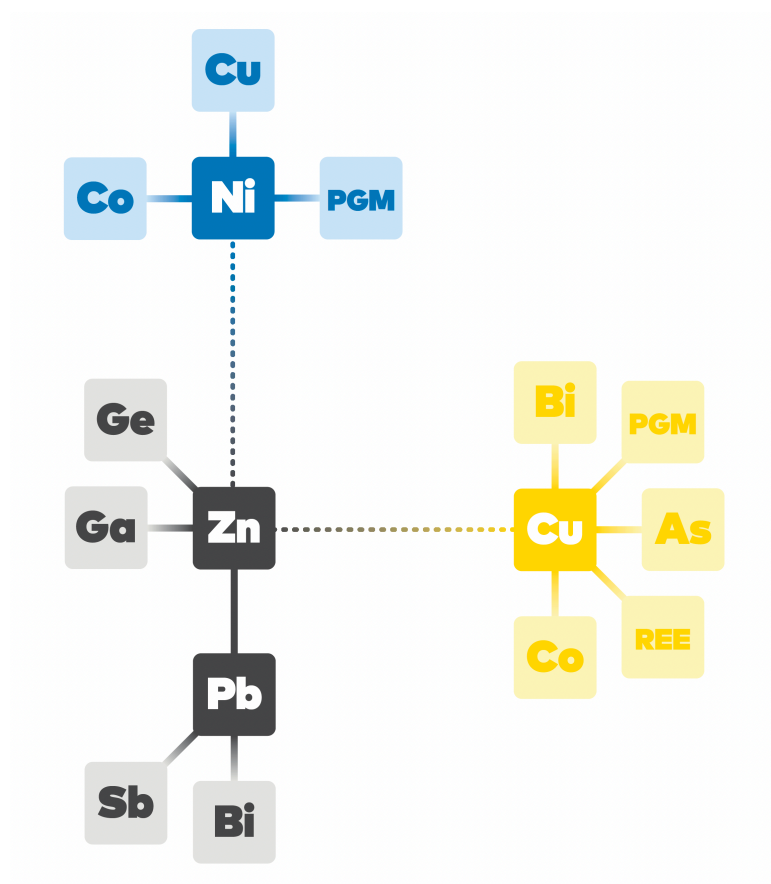


Figure 3.2 Typical elements that can often be found in common ores. As shown by the figure, the main CRM-elements Nickel and copper are sometimes associated with additional CRM-byproducts like antimony, arsenic, bismuth, cobalt, gallium, germanium, PGM and REE. Even silver, tellurium and selenium, elements that are considered CRMs by other powers than the EU, are commonly found in these ores. Illustration: Bergfald Miljørådgivere.

Boliden has a central position in the primary and secondary production of the CRMs copper, cobalt and nickel in the Nordics. The company operates several Nordic primary production plants based on mines in Sweden and Finland, including smelters in Rönnskär in Sweden, Kokkola and Harjavalta in Finland, and Odda in Norway. Boliden also has a secondary production capacity that can recover copper, cobalt and PGM in both Rönnskär where much WEEE is recycled and in

the smelter in Harjavalta. Nickel and associated CRMs can be recovered in the hydrometallurgical plants at Glencore Nikkelverk in Kristiansand in Norway and Nor Nickel at Harjavalta in Finland. Umicore also has a large cobalt recycling and refinery plant in Kokkola, Finland. All these companies have publicly expressed interest in getting hold of more recycled feedstock.

Important Nordic mines of copper, cobalt and associated CRMs include Atik, Garpenberg, Renström, Katrineberg and Kankberg in Sweden and Terrafame and Kevitsa, Finland.

The processing of ore at Bolidens smelters generates large amounts of waste that sometimes contains recoverable residual levels of CRMs. Boliden has tested technologies for additional recovery of metals from a large waste stream called jarosite sludge, although existing market conditions have so far made the implementation of this process economically unfavourable.

An important application of copper, nickel and cobalt and, by extension, potential feedstock for recycling operations are Li-ion batteries at the end of their product life. For this reason, battery recycling operations can be seen as an integrated part of the Cu-Co-Ni value chain, although other CRMs like lithium and graphite may also be recovered from black mass from discarded batteries. Companies that operate or plan to operate battery recycling plants including Northvolt in Sweden and Hydrovolt in Norway, will extract blackmass from discarded batteries that are then processed at Northvolt or other plants with similar recycling capacity. Terrafame operates a plant in Finland that will produce similar battery chemicals. Although Li-ion batteries contain lithium, no Nordic recycling capacity for this exists so far, although this is expected to become available in the near future. Keliber is however developing a lithium mine in Finland and considering additional technological recycling options.^[109]

Antimony is often alloyed with lead and is, therefore, indirectly recovered when lead is recycled. In the Nordics, this happens at the Boliden Bergsøe plant in Landskrona in Sweden.

Figure 3.3 shows an overview of the Nordic industry that can process copper, nickel and cobalt with associated byproducts. A detailed list of Nordic plants in this sector can be found in [Annex Table 2](#).

109. <https://www.sibanyestillwater.com/business/europe/keliber/>

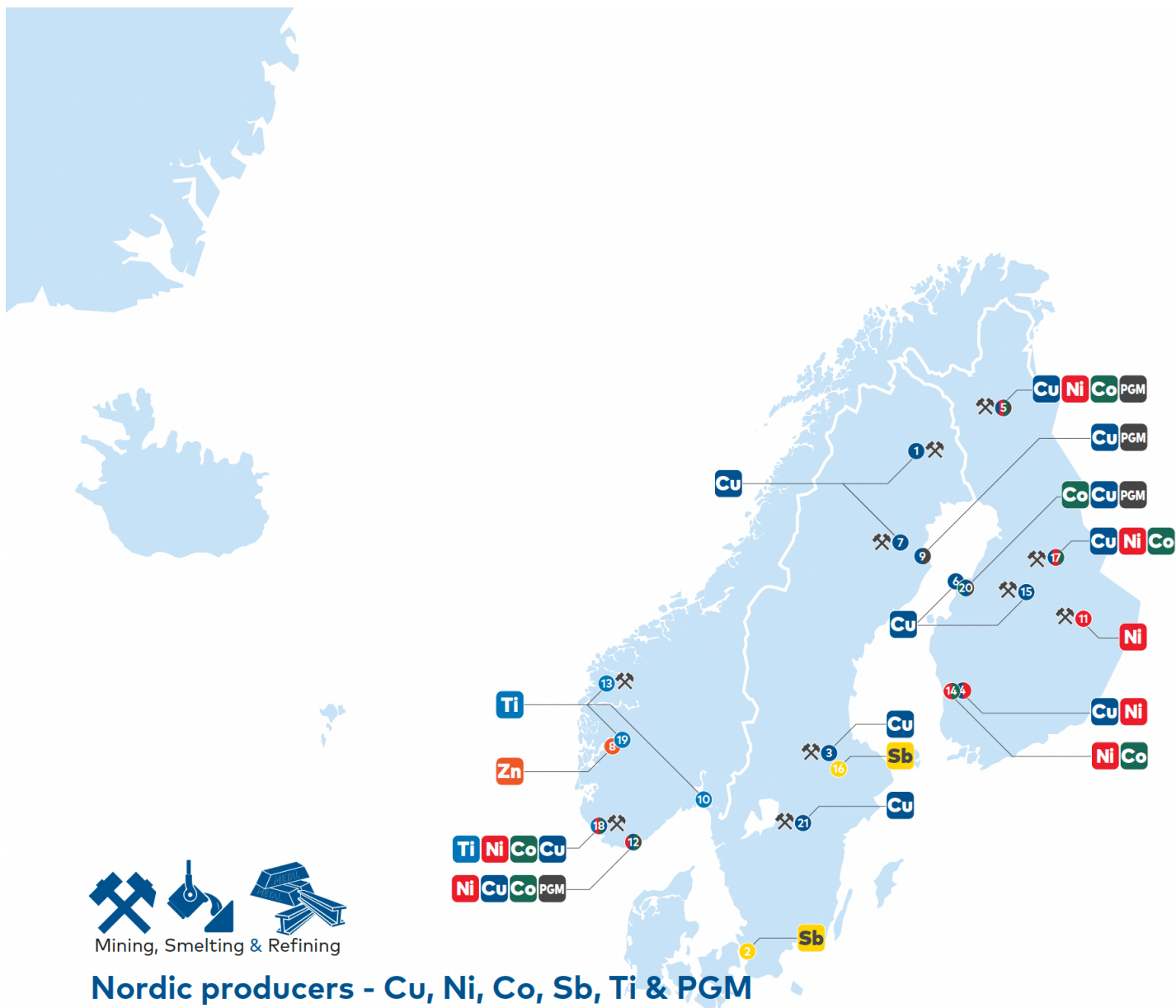


Figure 3.3 Overview of the Nordic industrial plants that can process copper, nickel and cobalt with some associated CRM-byproducts. Illustration: Bergfald Miljørådgivere.

3.3 Steel industry

Steel or iron is not currently listed as a CRM in Europe.^[110] Many steel alloys, however, contain CRMs that can be either lost or recovered when end-of-life steel is recycled. CRMs that are commonly used in steel alloys include nickel, niobium, manganese, silicon and vanadium. When sorted separately end of life steel alloys containing CRMs can be recycled in steel mills into secondary steel materials where CRM-components maintain their function. Alternatively, when mixed with other steel qualities, the CRM-components become too diluted to serve a functional role in the next-generation steel material or become a pollutant that lowers the quality of the product. Other waste streams like slags, dust and end-of-life batteries can also be used as a secondary CRM source in steel production, although mono-material recycling is preferred when possible.^[111]

There are many steel mills in the Nordics that could potentially adopt a more alloy-specific recycling operation. Steel mills in Sweden include Outokompo mills in Avesta, Degerfors and Nyby in Sweden, and Torino in Finland. SSAB operate blast furnaces at Oxelösund and Luleå. Different levels of alloying are performed at the EAF mills in, amongst others, Höganäs, Allmeia, Björneborg, Uddeholm and Ovako. There is also a secondary steel mill in Norway at Mo i Rana (Celsa Armeringsstål). Several minor and niche operators are also active.

One example of projects aiming at CRM-recycling of steel alloy components is the vanadium project of Neometals^[112] in Finland that aims at upgrading vanadium-containing blast furnace slags currently produced and landfilled in Sweden and Finland to a commercial ferrovanadium alloy. The Nordic steel industry could potentially be a platform for launching many similar CRM-recycling projects in the coming years that focus on either manganese, nickel or niobium.

The Nordic steel industry also has a close relationship with producers of ferroalloys such as ferrosilicon, ferromanganese and ferrochromium. Some waste fractions might also be returned to these plants for upgrading.

It should be noted that both the global and the Nordic steel industries are undergoing a substantial transformation. The traditional large blast furnace plants based on virgin iron ore and with limited support from smaller EAF based on scrap iron are shifting towards a new model. This involves direct the reduction of pig iron plants supported by a larger fleet of EAFs for steel production. This transformation will, on the one hand, demand new and more expensive iron feedstocks but will also reduce the availability of slags. Access to higher-purity pig iron will eventually increase flexibility in steel recycling.

Rebars from scrap – the CRM end station?

Some of the lost CRMs can be found if properly investigated, such as in typical end stations such as concrete or rebars. Indeed, rebars are globally heavily based on scrap steel, and a co-dependency has developed over time between the recycling industry and the rebar industry. The rebar industry gets secure, inexpensive and relatively consistent feedstock, and the recycling industry gets a secure offtake for the fractions of scrap steel that they are not able to sell into higher-grade steel segments.

110. China and South Africa classify iron ore as CRM, while some other countries are concerned with some specialty steels.

111. https://screen.eu/wp-content/uploads/2023/12/SCREEN2_factsheets_NICKEL-update.pdf

112. <https://www.neometals.com.au/en/business-units/core-divisions/vanadium-recovery/>

The requirements for rebars are mainly performance-based on elongation, tensile strength, etc. As such, the key international standards, such as ASTM A706, regulate the maximum levels of certain deleterious elements such as phosphorous, sulphur and copper. However, as rebars get the feedstock from mixed steel scrap, both performance-enhancing and performance-reducing alloys are included, and almost all of the periodic table is represented. When CRMs are represented in steel scrap and used in the production of rebar, it must be assumed that it is practically lost, as extraction, separation, and high grading will be very difficult.

The European production of rebars has been stable at around 12 million tonnes for many years, and we expect that this represents mostly also the consumption.^[113] Some import will come.

As the Nordic countries represent 10% of the European, we assume an average Nordic consumption of 1.2 million tonnes of rebars. In these rebars, approximately 3,000 tonnes of copper and 1,500 tonnes of nickel are dispersed,^[114] together with hundreds of tons of other CRMs such as tin, tungsten, tantalum and rare earths.^[115] With improved dismantling and sorting of steel alloys, some CRMs can be recycled instead of lost into the rebars.

Figure 3.4 presents an overview of the Nordic steel industry that could potentially recycle steel alloy CRM-components more efficiently. A detailed list of Nordic plants in this sector can be found in [Annex Table 2](#).

113. https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2023/FINAL_EUROFER_Steel-in-Figures_2023.pdf

114. Ramadan et al. Identification of copper precipitates in scrap based recycled low carbon rebar steel. Materials and design. 2017.

115. Odusote et al. Chemical and Mechanical Properties of Reinforcing Steel Bars from Local Steel Plants. J Fail. Anal. and Preven. 2019.



Nordic steel & vanadium producers

COMPANY	POTENTIAL CRM	PROCESS	COUNTRY
1. Alleima	Fe	Steel production	Sweden
2. Bjørneborg	Fe	Steel mill	Sweden
3. Celsa Armeringsstål, Mo i Rana	Fe	Sec. steel smelter and foundry	Norway
4. HYBRIT	Fe	Steel mill	Sweden
5. Höganäs	Fe	Steel production	Sweden
6. Neometals	V	Recycling V from steel slag	Finland
7. Outokumpu Avesta	Fe	Steel mill	Sweden
7. Outokumpu Avesta Operations	Fe	Steel production	Sweden
8. Outokumpu Degerfors Operations	Fe	Steel production	Sweden
9. Outokumpu, Nyby Operations	Fe	Steel production	Sweden

COMPANY	POTENTIAL CRM	PROCESS	COUNTRY
10. Outokumpu, Tornio Works	Fe	Steel production	Finland
11. Ovako	Fe	Steel production	Sweden
12. Ovako Hofors	Fe	Steel mill	Sweden
13. Ovako Imatra	Fe	Steel mill	Finland
14. Ovako Smedjebacken	Fe	Steel mill	Sweden
15. SSAB Borlänge	Fe	Steel production	Sweden
16. SSAB Luleå	Fe	Steel mill	Sweden
17. SSAB Oxelösund	Fe	Steel mill	Sweden
18. SSAB Raahé	Fe	Steel mill	Sweden

Figure 3.4 Overview of important Nordic steel mills. Illustration: Bergfald Miljørådgivere.

3.4 Silicon industry

There is a significant Nordic primary production capacity for silicon metal that currently covers 35% of the EU supply need.^[116] Several Nordic smelters produce silicon or silicon alloys like silicon manganese, silicon carbide, silicon nitride or ferrosilicon. The largest contributor is Elkem with, operating plants at Bjølvfossen, Bremanger, Rana, Salten and Thamshavn in Norway and Akranes in Iceland. Other producers include Finnfjord and Wacker Chemicals in Norway and BakkiSilicon in Iceland. Plants that produce silicon metal or silicon alloys can, in many cases, be converted between metal and alloy production. Fives production of silicon carbide can also be mentioned, as this plant in periods has looked at secondary raw materials while simultaneously producing high-end materials for the electronics industry. This plant may increase its use of some secondary feedstocks.

Secondary silicon production is absent in the Nordics and worldwide. However, R&D efforts toward an industrial process that can recycle silicon from waste materials like discarded solar panels are ongoing, and the Norwegian primary producers may have a role in this development. Some projects are looking at recycling silicon from slag. Given the right incentives, the Nordic silicon industry, with its technology base, expertise, and market position for primary products, should have a good platform from which a secondary value chain could be developed.

As silicon is a CRM because of a certain lack of refining capacities in the IT and solar market, and not due to lack of access to the element, recycling might play a lesser role for silicon than for most other CRMs.

A new plant for recycling silicon swarf from solar cell production is under development in Norway. Silicon swarf and aluminium swarf are mixed and extruded under high pressure to an aluminium-silicon alloy.^[117]

3.5 Graphite production

Natural graphite has been mined from close to 100 Nordic locations over the last centuries, but currently, only one mine is operational – the MRC Skaland Graphite at Senja in Norway, which supplies 9% of the current European consumption.^[118] There are existing mines in care and maintenance that could be restarted, as well as several tens of projects under development.

Synthetic graphite is produced at three locations: the experienced Superior Graphite plant in Sweden and the new Vianode plant in Norway. In addition, a Chinese plant is planned in association with the Northvolt plant in Sweden.

Several companies have proposed recycling graphite from waste sources like end-of-life batteries or discarded industrial refractories.

So far, the Nordic battery recycling projects have focused on recovering metals like nickel and cobalt, but graphite recycling could become possible in future recycling solutions.

Another option is the production of synthetic graphite from CO₂ or another carbon source.

Bergen Carbon Solutions and Vianode are examples of start-ups developing graphite products based on this technology.

116. https://screen.eu/wp-content/uploads/2023/12/SCREEN2_factsheets_SILICON_METAL-update.pdf

117. <https://nuvosil.com/>

118. https://screen.eu/wp-content/uploads/2023/12/SCREEN2_factsheets_GRAPHITE_V1.pdf

Graphite is not a homogenous commodity but is traded in different types and qualities. Graphite for advanced technological applications like Li-ion batteries require quality levels that secondary and synthetic graphite materials have struggled to reach so far. Superior Graphite is an example of a Swedish company that is working towards closing the quality gap between natural and synthetic graphite for several application areas, including batteries.^[119] In the meantime, there is a market for synthetic graphite (1.5 Mt) that already exceeds the natural graphite market at 1.2 Mt, and the improved quality for future synthetic graphite is expected to widen this difference in market share even further.^[120]

3.6 Manganese industry

Manganese can be recovered from waste streams from the production and end-of-life products like steel alloys and batteries. There is a significant Nordic primary production capacity for manganese alloys that currently covers 32% of the EU supply need.^[121] This capacity is provided by the three Eramet plants located in Sauda, Kvinesdal and Herøya, and by the Ferroglobe plant located in Mo i Rana, all located in Norway. These plants produce primary ferro-manganese and silicon-manganese and are involved in some recycling projects based on industrial dust and fines. There are also plans to establish a manganese sludge recycling plant in a Scandinavia. The Nordic manganese industry could potentially play an integral role in setting up a Nordic industry for the production of secondary manganese products or manganese materials for batteries.

There has until recently been a recycling plant for high-manganese steels, in Norway. While ferromanganese alloys normally have >80% Mn, and regular steels have 0.5–1% Mn, this plant operated in the niche market for 15–25% Mn-steels. However, this plant was closed in 2023. While parts of this recycling plant have already been dismantled and exported out of Europe, some parts are still left and could be restarted.

Figure 3.5 shows an overview of the Nordic industry that can process silicon, manganese, graphite and lithium. A detailed list of Nordic plants in this sector can be found in [Annex Table 2](#).

119. <https://superiorgraphite.com/products/resilient-graphite/>

120. https://screen.eu/wp-content/uploads/2023/12/SCRREEN2_factsheets_GRAPHITE_V1.pdf

121. https://screen.eu/wp-content/uploads/2023/08/SCRREEN2_factsheets_MANGANESE.pdf

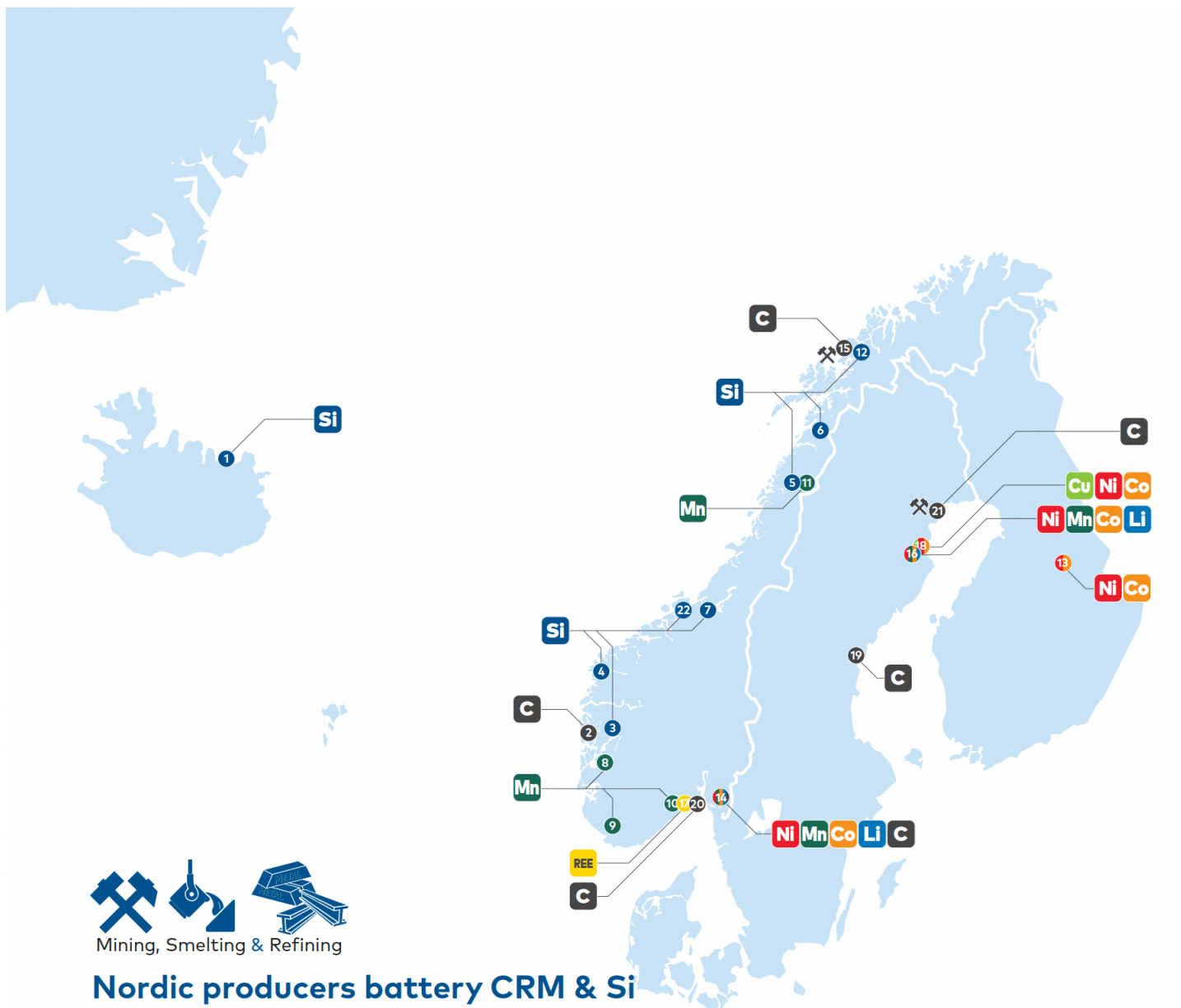


Figure 3.5 Overview of the Nordic industrial plants that can process silicon, manganese, graphite and lithium with some associated CRM-byproducts. Illustration: Bergfald Miljørådgivere.

3.7 The phosphate industry

The largest consumer of phosphates is the agricultural sector, where phosphate is a main chemical component of synthetic fertiliser. Finland is the only Nordic producer of rock phosphate and currently supplies 18% of the European consumption from the Yara Siilinjärvi mine.^[122] A significant off-taker of rock phosphate is the Nordic fertiliser industry dominated by Yaras production plants at Herøya and Glomfjord in Norway and Kokkolan, Särkikanta and Uudenkaupungin in Finland.

Currently, all synthetic phosphate fertiliser production is based on mined rock phosphate, imported from outside of Europe. Primary rock phosphate could, to a large extent, be replaced by secondary phosphate from mining byproducts and recycling. There is a large biogas sector in the Nordics that, through anaerobic digestion, converts different organic waste streams into biogenic methane and a phosphate-rich bio residue that is currently used locally as organic fertiliser and could potentially be utilised as a secondary phosphate feedstock for synthetic fertiliser. Another source of secondary phosphate is wastewater, where dissolved phosphate may be captured in the form of struvite as done at the water cleaning plant of HIAS in Hamar, Norway. A third source of secondary phosphate comes from ash from incineration of organic waste or biomass. Ragnsells is building a plant in Helsingborg, Sweden, based on their Ash2Phos-technology that will recover phosphate from incinerated sewage sludge.^[123] The Swedish mining companies LKAB and Grängex plan to process apatite-rich flotation sludge into phosphate feedstocks. This has been done before – for several decades, about half of the Nordic fertiliser production was based on secondary feedstocks. This stopped when the Soviet Union collapsed and swamped the market with low-cost virgin material. When and if any new phosphate recycling and byproduct capacity is established in the Nordics, it must also be protected from undue market manipulations from large market players.

3.8 Rare earth element production

Several new Nordic mining projects are looking at rare earth element extraction from Nordic locations, including LKAB at Per Gejer and Leading-Edge Materials at Norra Kärr in Sweden. The largest Nordic REE mineral reserves have so far been identified at the Fensfeltet in Norway, currently under development by the company Rare Earth Norway. There are also projects developing REE-recycling operations from tailings including Grangex at Grängesberg and LKAB with its ReeMap-project at Luleå in Sweden and Yara from the phosphate mine at Siilinjärvi in Finland.

Many junior mining companies talk about REE levels in their resources, but the probability of any of these coming into production is, at best, limited.

Although there is currently no Nordic REE recycling capacity from post-consumer waste streams, a LREE processing plant recently built at Herøya in Norway could potentially be expanded to produce secondary REE-concentrates. Indeed, the newly built REEtec plant has successfully tested the recycling of several post-consumer REE waste streams. However, several bottlenecks in the sorting and recovering REE-rich post-consumer wastes must be overcome before secondary materials become a relevant and significant source. Many relevant R&D projects are ongoing in several Nordic countries to overcome these constraints.

122. https://screen.eu/wp-content/uploads/2024/01/SCREEN2_factsheets_PHOSPHATE-update2.pdf

123. <https://avfallsbransjen.no/2024/05/14/ragn-sells-far-utslippstillatelse-for-fosfor-gjenvinningsanlegg/>

3.9 Titanium production

Some Nordic titanium alloy production capacity exists, mainly in Finland.^[124] Titanium swarf from the machining of components is routinely used as feedstock for alloy production (amongst other aluminium alloys) and should be regarded as recycling, even if it is downcycling. By using swarf in alloy production, the use of virgin sponge is avoided for those applications.

There is also significant production of titanium ore concentrate in the form of ilmenite (FeTiO_3) produced at Titania and rutile (TiO_2) produced at Nordic Mining in Norway and could serve as raw material for a Nordic titanium plant.

3.10 Platina Group Metal Production

There are several essential stakeholders in PGM production and recycling in the Nordics. Glencore in Norway and Nor Nickel in Finland extract and refine PGMs from imported nickel ores as byproducts. Part of the production in Finland comes from domestic concentrates. Finland also has the largest undeveloped PGM resources in the Nordic region, amongst others, and the largest and most important Sakatti mine in the north of the country.

Several companies are also active in different levels of recycling. Boliden extracts some PGMs from WEEE, as well as from mining byproducts. Most advanced is K.A. Rasmussen in Norway, with advanced recycling and processing of separated PGMs from several complex waste fractions. These plants may be expanded both in complexity and volume.

124. https://screen.eu/wp-content/uploads/2024/01/SCREEN2_factsheets_TITANIUM_V1.pdf

4. Instruments and measures for better CRM-recycling in the Nordics

CRMA requirements

This chapter describes potential measures and instruments for how CRM-recycling in the Nordics can be increased and improved. Based on a set of criteria listed below, 85 possible measures have been identified, of which 16 have been given an extended description in this chapter. A complete list of all identified measures can be found in [Appendix Table 2](#). The criteria for selecting potential measures include:

- High expected benefit in terms of increased CRM-recycling
- Supports solutions with a Nordic competitive advantage
- Relevance for as many Nordic countries as possible
- High cost-efficiency
- Addresses as many milestones as possible for increased CRM-recovery
- Contributes to resource utilization of the most/largest/richest possible waste streams
- Addresses recovery of as many CRMs as possible

Article 26 of CRMA requires member states to adopt and implement a national program that contains measures designed to help the EU reach its new targets for improved CRM-circularity. These targets are listed in Article 26 and include:

- a. improved technological progress and CRM-resource efficiency;
- b. increased waste prevention and re-use and repair of products and components with relevant critical raw materials;
- c. increased collection, sorting and processing of waste with relevant critical raw materials recovery potential, including metal scraps, and ensuring their introduction into the appropriate recycling system to maximise the availability and quality of recyclable material as an input to critical raw material recycling facilities;
- d. increased use of secondary critical raw materials, including through measures such as taking recycled content into account in award criteria related to public procurement or financial incentives for the use of secondary critical raw materials;
- e. increased technological maturity of recycling technologies for critical raw materials and promoting circular design, materials efficiency and substitution of critical raw materials in products and applications, at least by including support actions to that effect under national research and innovation programmes;

- f. ensure that measures are in place to equip their workforce with the skills needed to support the circularity of the critical raw materials value chain, including measures on upskilling and reskilling;
- g. where financial contributions are to be paid by the producer following its extended producer responsibility obligations under national law under Article 8(1) of Directive 2008/98/EC, promote the modulation of such financial contributions to incentivise a larger share of secondary critical raw materials recovered from waste, recycled in line with relevant Union environmental standards, to be contained in products;
- h. ensuring that critical raw materials that are exported after ceasing to be waste fulfil the relevant conditions following Directive 2008/98/EC and other relevant Union laws; and
- i. where relevant, support the use of Union quality standards for recycling processes of waste streams containing critical raw materials.

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- e. increased technological maturity of recycling technologies for critical raw materials and promoting circular design, materials efficiency and substitution of critical raw materials in products and applications, at least by including support actions to that effect under national research and innovation programmes;
- f. ensure that measures are in place to equip their workforce with the skills needed to support the circularity of the critical raw materials value chain, including measures on upskilling and reskilling;
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- h. ensuring that critical raw materials that are exported after ceasing to be waste fulfil the relevant conditions following Directive 2008/98/EC and other relevant Union laws; and
- i. where relevant, support the use of Union quality standards for recycling processes of waste streams containing critical raw materials.

Paragraphs (a), (c), (d), (e), (f) and (g) of Article 26 are most relevant for CRM-recycling and have been considered as selection criteria when evaluating potential measures and instruments.

Paragraph 2 of Article 26 allows this program being either set up as an independent plan, or to be incorporated as an integrated part of existing national plans for waste management or waste prevention. Regardless the form of the program, Article 2 also requires the program to be reviewed and updated where necessary within five years after its adoption.

To promote increased collection and recycling of CRM-containing waste Paragraph 3 allows for measures that include financial incentives like discounts, monetary rewards, or deposit-refund systems.

Paragraph 4 requires measures to be designed not to create trade barriers or conflicts with the Treaty of European Union.

Paragraph 5 contains specific requirements regarding mapping and reporting the amounts of CRMs contained in components removed from collected WEEE and refers to delegated acts yet to come for more detailed instructions on how this shall be done. The first reporting period will be the first full calendar year after adopting CRMA.

Paragraph 6 requires states bound by CRMA to submit an annual report to the EU commission that includes a status for the national program on CRM-circularity and the progress on implementation of individual measures.

Paragraph 7 provides information about future delegated acts that the Commission will present, which will contain a more detailed description of which products, components and waste streams shall be considered for CRM-recycling.

Overall recommendations

The national programs for increased circularity and security of supply of critical raw materials should emphasize the already existing industrial potentials. The Nordic countries have significant natural CRM-resources, substantial CRM-containing waste volumes and an operating industrial platform able to build new circular industries.

The program is advised to set up milestones for mapping waste streams with CRM-recovery potential, systems for cost-effective collection of waste streams that can be CRM-recycled, and improved recycling processes.

Each country can only be expected to establish specific recycling operations for some individual CRMs and should focus on establishing or improving national value chains for recycling of a limited number of CRMs where national competitive advantages can be identified. These advantages include available waste streams that can be recycled and existing industrial technology, competence and infrastructure that may facilitate new CRM-recycling operations.

Under each milestone, a list of measures that are considered necessary for reaching the milestone should be given.

Suggested milestones include:

1. A system that makes it possible to identify waste streams with CRM-recycling potential.
2. A system for cost-effective and efficient collection of waste streams with CRM-recycling potential.
3. A system for separating materials enriched with CRM from other materials in the waste stream.
4. A recycling technology that allows for the recovery of all relevant CRMs at acceptable recovery rates.
5. Market conditions that are economically sustainable for all links in the value chain.

Figure 4.1 summarises the measures described in this chapter and shows at what point they are expected to take effect in the value chain.

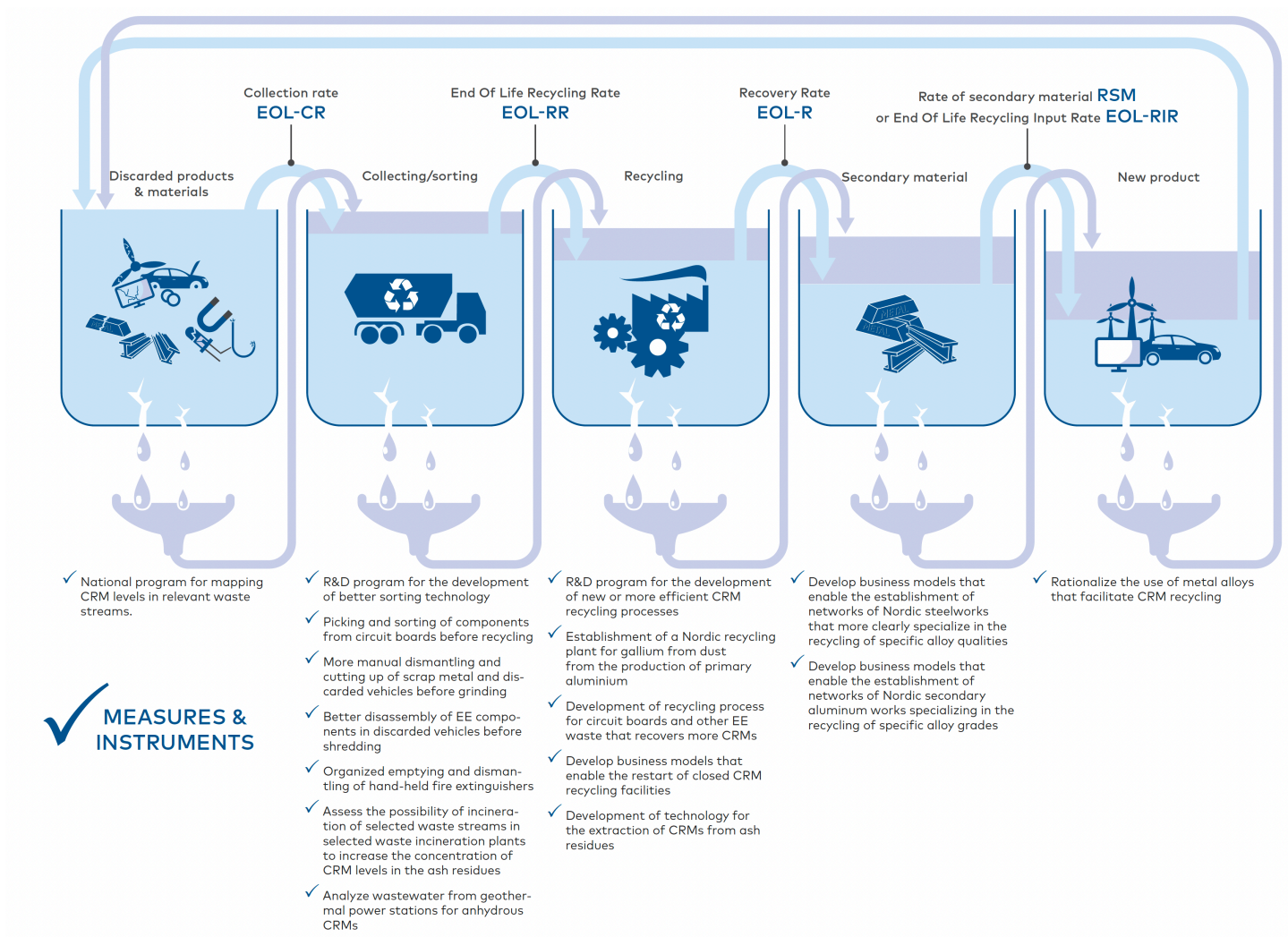


Figure 4.1 Overview of measures to improve Nordic CRM-recycling described in this chapter.

Illustration: Bergfald Miljørådgivere.

4.1 Mapping CRM-waste streams

Recycling CRMs requires knowledge about which waste streams contain recoverable levels of CRMs. Although some information about CRM-levels and other relevant parameters already exists for some waste streams, there is no systematic and comprehensive oversight, and for many Nordic waste streams, these issues are too poorly examined to provide a clear understanding of the CRM-recycling potential for specific waste streams. A systematic and cost-efficient system for mapping CRM-recyclable waste streams is, therefore, a necessary step in a national effort to increase CRM-recycling. For several of the relevant waste streams, the CRM-composition will change over time, so in addition to initial mapping some level of monitoring of relevant parameters will often be necessary later.

4.1.1 National program for mapping CRM-levels in relevant waste streams.

Identifying waste streams suitable for CRM-recycling requires a minimum of information on the chemical composition of the waste and the physical properties that affect how recycling occurs. For many materials and waste streams, such data are limited or non-existent. A national programme for mapping this information about relevant waste streams may be a way to meet the requirements described by articles 26 and 27 of CRMA regarding these issues. Such a programme can provide a standardised and systematic way for identifying waste streams with CRM-recycling potential and indicate how a potential recycling process may best be designed.

The program should include guidelines on the following topics:

- Which waste streams are included in the program
- Which properties are to be examined
- Which test procedures should be followed when examining a waste stream

Until specified by the EU Commission later, the following waste streams should be considered included in the program:

- Active and historic landfills for tailings from mining operations
- Active and historic landfills for industrial waste from metallurgic and mineral processing
- Active and historic landfills for waste expected to contain significant amounts of the following waste categories: WEEE, metallic scrap, fluff and fines from shredding operations, tyres and ash from incineration operations
- Active and historic landfills for alum shale

To ensure a common practice regarding sampling and analysis of different waste streams, national guidelines should describe how this shall be done and detail the competence necessary for performing these tasks. The guidelines for CRM-mapping should include a description of which waste streams are to be included in the mapping, which parameters are to be monitored beyond CRM-concentrations, and which analysis techniques should be applied, as well as how

sampling and data recording are to be carried out. The requirements for mapping waste streams with recoverable CRM should be considered as minimum requirements, and additional tests should be encouraged if this is considered relevant for understanding the full resource potential.

Ownership of the data and public access rights should also be clarified. How the mapping program can be included as part of a more complete description of the CRM-materials' life cycle movement through the technosphere as a broader knowledge base supporting the revision of future CRM-policies should also be considered. Collected data should be registered in a national database that has been set up in line with CRMA guidelines. Instead of an individual database for each country, a common database for the whole Nordic region should be considered. A common Nordic database will be beneficial when assessing cross-border CRM-recycling potentials.

All relevant waste streams that are expected to contain recyclable levels of CRMs potentially should be included in the mapping program. This should include tailings and other mineral waste in both active and historic landfills and landfilled waste from industrial and public landfills, including both active and closed sites.

All waste streams should be tested for concentrations of CRMs and possibly other relevant raw materials like indium, tin and molybdenum with high economic importance- and supply risk score, although just below the current threshold for being classified as CRM by the EU. Several waste streams contain low levels of valuable non-CRM metals such as gold and silver. As sampling and reporting are more costly than analysis, including valuable metals in mapping would often be relevant, as even minor content of gold or silver could make a CRM-recovery operation more economically viable. Measured CRM-concentrations in the waste material should be compared to a set of CRM-specific threshold values considered the lowest possible concentration relevant for a potential recycle operation. The threshold values should be set at the lowest possible level where potential recycling may be applicable, and for waste streams where these thresholds are exceeded for one or several CRMs, an additional and more detailed description of the waste stream should be required. Based on the levels of CRMs in ore from which these CRMs are produced today, a set of indicative thresholds values is suggested in Table 4.1. These values should be considered as an initial estimate. They may change drastically depending on other suitability conditions, the concentrations of other recoverable CRMs and the volume of the waste stream.

Table 4.1 Suggested threshold values that should trigger a more extensive description of CRM-recycling in a waste stream Source: Bergfald Miljørådgivere.

Critical raw materials	Minimum concentration for recycling
Antimony	>1%
Arsenic	>10%
Aluminum	>50% alumina
Baryte	>10%
Beryllium	>10%

Bismuth	>1%
Boron	>10%
Cobalt	>0.2%
Coking coal	Not considered relevant
Copper	>0.3%
Feldspar	>50%
Fluorspar	>2%
Gallium	>100 ppm
Germanium	>100 ppm
Graphite	>15%
Hafnium	>2%
Helium	
Heavy Rare Earth Elements (Dysprosium)	>100 ppm
Heavy Rare Earth Elements (Erbium)	>1%
Heavy Rare Earth Elements (Holmium)	>0.5%
Heavy Rare Earth Elements (Lutetium)	>50 ppm
Heavy Rare Earth Elements (Terbium)	>50 ppm
Heavy Rare Earth Elements (Thulium)	>10%
Heavy Rare Earth Elements (Ytterbium)	>1%
Heavy Rare Earth Elements (Yttrium)	>10%
Light Rare Earth Elements (Cerium)	Overproduction currently being landfilled
Light Rare Earth Elements (Europium)	>1%
Light Rare Earth Elements (Gadolinium)	>1%
Light Rare Earth Elements (Lanthanum)	>20%

Light Rare Earth Elements (Neodymium)	>1%
Light Rare Earth Elements (Praesodymium)	>0.5%
Light Rare Earth Elements (Samarium)	Overproduction currently being landfilled
Lithium	>1%
Magnesium	Not suitable for magnesium production
Manganese	>30%
Nickel - battery grade	>0.5%
Niobium	>0.2%
Phosphate rock	>2%
Phosphorous	Not considered relevant
Platinum Group Metals (Iridium)	>0.01 ppm
Platinum Group Metals (Palladium)	>0.2 ppm
Platinum Group Metals (Platinum)	>0.5 ppm
Platinum Group Metals (Rhodium)	>50 ppb
Platinum Group Metals (Ruthenium)	>10 ppm
Scandium	>1000 ppm
Silicon metall	>90%
Strontium	>10%
Tantalum	>100 ppm
Titanium	>10%
Tungsten	>500 ppm
Vanadium	>1%

Information collected from a waste stream should be reported through a scheme containing at least the following report elements:

- A description of the location(s) of the waste stream, from where it arises, estimated amounts and how it may be collected, if possible, with a map showing sampling points;
- Number of test samples collected, what analysis technique has been applied and which laboratory (with its accreditation details) has performed them;
- Test results showing the concentration of individual CRMs and, where applicable, other valuable components;
- A description of the variations in the CRM-concentrations (maximum and minimum values in addition to mean and median values);
- Short comments on any significant variations in CRM-concentrations compared to earlier data, if available;
- Describe other relevant properties of the waste stream, such as bulk density, physical characteristics and smell, water content, hazardous aspects like heavy metal concentrations, etc.; and
- Contact person for the request for additional information.

Potential for recycling of critical raw materials

Knowledge of CRM-content and associated physical properties is necessary for identifying waste streams that may be relevant for CRM-recycling and an initial assessment of which recycling technology could be relevant for such recycling. All CRMs can be found in specific waste streams, and a system for mapping enhanced levels of individual CRMs in different waste streams can hence lead to new CRM-recycling operations and/or increased recycling of CRMs. Until such a mapping has been performed, however, quantifying the recycling potential for individual CRMs is challenging.

The first report in this report series^[125] estimated a hypothetical CRM-recycling potential from Nordic waste streams at around 900,000 tonnes per year, not including legacy waste dumps and tailings sites. However, as no recycling process achieves 100% efficiency – many operating significantly below this – the realistic and practical recycling potential is thus considerably lower. Nevertheless, it is realistic to plan for several new industrial recycling operations and to expect the recycling of tens of thousands of tonnes of CRMs, provided a reasonable implementation of the CRMA.

Barriers and possible means of actions/instruments

Based on current regulations, many waste streams have already been analysed for a limited number of chemical compounds. These regulations almost exclusively focus on monitoring hazardous compounds like heavy metals and toxic organic compounds. As long as no regulations have required CRM-testing so far, the additional economic costs and efforts associated with such testing have probably been prohibitive for voluntarily undertaking such tests.

125. <https://pub.norden.org/temanord2024-513/temanord2024-513.pdf>

Mandatory and standardised CRM-testing of relevant waste streams should, therefore, be introduced either as an additional requirement in an updated operation permit or as an added legal requirement in national regulations for pollution, mineral extraction or waste management.

Socio-economic impact

Implementing a programme to map CRM-levels in relevant waste streams will enable the identification of CRM-recycling of significant feedstocks, which might otherwise remain unutilised.

Implementing a national system for mapping CRM-levels in relevant waste streams will add additional costs to companies operating landfills or waste-generating processes and require public funding of competent agencies tasked with mapping CRM-levels in historic waste materials where no legal ownership can be established.

Mapping the CRM-recycling potential of waste at a typical landfill is estimated to require two days' work (15 hours) for sampling and reporting. Assuming an hourly cost of DKK 1000, this means work costs of DKK 15,000, per site. A complete IPC analysis that includes all relevant CRMs is estimated to cost around DKK 20,000, depending on how many samples and the type of agreement with the laboratory. Suppose that one hundred of the most relevant landfills in each category are selected for mapping in Sweden, Finland, and Norway, 25 sites are selected for the same purpose in Denmark and Iceland. In that case, this will bring the total costs of this mapping to DKK 12.3 million. Assuming each examined waste stream contains, on average, 10,000 tonnes, the cost per tonne of waste will be DKK 3.5 per tonne. Additionally, costs are associated with receiving and incorporating reported data in a central database not included in this evaluation.

The measure is not expected to cause significant environmental impacts of any kind.

Description and Prerequisites

CRMA contains several requirements and guidelines for CRM-levels in relevant waste streams that should be mapped.

Article 26 c requires member states to design and implement measures to "increase the collection, sorting and processing of waste with relevant critical raw materials recovery potential, including metal scraps, and ensure their introduction into the appropriate recycling system, to maximise the availability and quality of recyclable material as an input to critical raw material recycling facilities:". This requires knowledge about CRM-levels in relevant waste streams.

As of December 2024, CRMA does not contain a complete and detailed description of how CRM-waste streams should be mapped. Delegated acts addressing this issue will follow in the coming years, according to Article 26, paragraph 7. CRMA does, however, address the mapping of CRM-levels in some waste streams, including WEEE (Article 26, paragraph 5) and extractive waste (Article 27)

According to Article 27 of CRMA all operators of extractive industries that are required to draw up a waste management plan as described in the *Directive for management of waste from extractive industries*^[126] must henceforth also provide the relevant national governmental authority with a preliminary economic assessment of the potential recovery of CRMs from both extractive waste being generated and already stored on site unless it can be demonstrated with a high degree of certainty that these waste streams do not contain technically recoverable CRMs.

126. <https://eur-lex.europa.eu/EN/legal-content/summary/management-of-waste-from-extractive-industries.html?fromSummary=19>

Paragraph 2 of Article 27 states that these economic assessments must include a description of CRM-concentrations in extractive waste streams.

Paragraph 4 of Article 27 requires all states bound by CRMA to set up a database of closed extractive waste facilities that may contain recoverable CRMs. The database shall contain information that includes volumes of different waste streams together with associated CRM-concentrations.

According to paragraph 5 of Article 27, this database must “be put in place by 24 November 2026, and all the information shall be introduced in that database by 24 May 2027. It shall be made available in a publicly accessible and digital form and updated at least every three years to incorporate additional available information and newly closed or newly identified facilities.”

As a part of setting up this database, paragraph 7 requires extractive waste facilities that lack the necessary CRM-data to conduct additional geochemical sampling. For extractive waste facilities where preliminary data indicate potentially economically recoverable quantities of CRMs, a more detailed sampling with subsequent chemical and mineralogical characterisation involving core logging or equivalent techniques is required.

If possible, the recordings in the database should be based on the United Nations Framework Classification for Resources (UNFC).^[127]

Some prerequisites considered necessary for successful implementation are clear guidelines and supplementary guidance drawn up for how the mapping is to be carried out. It is also important that the work is followed up as part of the environmental authorities' supervision.

Other variants of the measure

In principle, mapping CRM levels and other recycling-related properties of relevant waste streams can be organised differently. One way would be to carry out a state-organised and funded project where a group of professionals with the necessary expertise visits relevant sites for inspection and sampling of applicable waste streams and records the results in a database open for public inquiry. Alternatively, the same tasks can be organised through a national program where the waste operator or owner is required to carry out the necessary investigations as part of their operating license. In many cases, the waste owner already needs to regularly measure the concentration of heavy metals and other environmental pollutants as part of their operating permit, and corresponding CRM-measurements can be integrated into existing environmental monitoring programs. Therefore, this second approach is considered to be both the most practical and cost-effective, and thus, the recommended scenario described in this chapter.

The measure of mapping CRM-levels in relevant waste streams can also be expanded and reduced in scope compared to the description in this chapter. Legacy waste can, for instance, be excluded from the first phase of mapping, and the number of compounds analysed can be limited to only CRMs and not include other chemical elements of economic importance.

As electronic products that later become WEEE are important to use for CRMs, and much of the Nordic consumption of electronic products is based on import from Asia, it could be considered to mandate and finance that the Environmental Agencies of the Nordics carry out an extensive content characterisation of some products in annual check, as the agencies currently do with some products regarding possible toxic and hazardous chemicals.

127. https://unece.org/sites/default/files/2023-10/UNFC_ES61_Update_2019.pdf

4.2 Collection and pre-processing

Collection and pre-processing are crucial parts of the value chain for producing secondary CRMs. Without a rational and cost-effective collection system, waste streams necessary as feedstock cannot reach the recycling operation, and without necessary pre-processing, the feedstock will not have the required quality for successful CRM-recovery.

4.2.1 R&D program for the development of better sorting technology.

Many products are becoming more complex regarding the number of components and different types of materials they contain. This is especially apparent in electronic products and vehicles, making recycling such products more challenging due to technical barriers against separating individual components and sorting sufficiently homogenous material fractions suitable for high-quality recycling. Many CRMs with recovery potential are lost due to the absence of sorting technologies that efficiently separate CRM-rich fractions or components from the remaining parts of the waste stream. For example, magnets and many batteries are lost due to built-in product design solutions that make component picking difficult. In some cases, these discarded products are not even shredded but incinerated due to safety concerns. For this reason, an urgent need is to develop automated separation and sorting solutions for better disassembling, e.g. WEEE and scrapped vehicles. Also, for metal alloys, there is a need for better sensory solutions that enable more accurate separation of specific alloys.

There are automatic waste sorting solutions, including robots, on the market already.^{[128][129][130]} The consensus amongst WEEE waste operators is that these technological options are neither flexible nor reliable enough to provide optimal separation of CRM-specific components and alloys. Examples of challenges that need to be overcome include discarded products that cannot be disassembled without breaking them due to the welding or glueing of components, clusters of WEEE products that cannot be separated because they are entangled in cables and a mixture of alloys that cannot be separated because the sorting system cannot recognise the specific material signature.

When stripping discarded EE-products of individual CRM-rich components like magnets, batteries and PCBs, often these components cannot be separated because the product is glued or welded together in a way that makes non-disruptive dismantling difficult and time-consuming. A parallel challenge occurs when scrapping EOL-vehicles where WEEE components are often removed after shredding because they are in a hard-to-reach position, making disruptive dismantling challenging and time-consuming.

When individual alloys in scrapped vehicles, WEEE and shredded scrap metal are not separated, the recycling process combines these alloys, resulting in the loss of minor CRM-alloy components such as manganese, nickel, and vanadium.

Ongoing technology innovations provide hope for better automatic waste-sorting solutions in the future that can deal with these challenges. In existing automatic waste sorting solutions, machine vision uses cameras and artificial intelligence to identify and sort materials with CRM-recovery potential. It typically operates by analysing images of waste components that pass on a conveyor belt and detecting and instructing sorting various waste materials, including

128. <https://wasterobotic.com/technology/>

129. <https://recycleye.com/swEEP-kuusakoski-ai-weee-sorting/>

130. <https://www.tomra.com/waste-metal-recycling/applications/metal-recycling/e-scrap>

differentiating between main metals like iron/steel, aluminium and copper. More exact discrimination between specific alloys is only possible to a limited degree, and the cost of sorting is higher than the economic premium of alloys. Integrating more advanced element-specific sensor techniques, like X-ray Fluorescence (XRF), enables the identification of more specific alloy signatures. It is also crucial that future automated waste sorting systems can read the coming product pass signature of the EU.

Another technical challenge that must be addressed is more precise and flexible mechanical separation techniques. Existing sorting solutions often rely on separation through pneumatic systems where a burst of air blows selected waste fragments into separate containers, or a robot arm picks out selective material fractions. So far, these systems cannot free discarded products and components from associated cables they are entangled in or stuck to. Such solutions are not capable of dismantling single CRM-specific components from the discarded product array they are a part of. Future separation solutions should be able to handle such tasks that so far can only be performed using manual labour.

Potential for recycling of critical raw materials

Better pre-treatment of WEEE, EOL-vehicles and metal scrap can generate larger and more pure waste streams to recycle more secondary CRM-materials of higher quality. Today, only primary construction metals like steel, aluminium, and some magnesium are sorted out using scrap metal treatment. At the same time, minor CRM-alloy components often remain mixed in ways that make efficient recycling difficult or impossible. Through better separation and sorting methods for metal scrap and WEEE, significant amounts of CRMs lost in today's treatment can instead be harvested for functional roles in new product lives.

Barriers and possible means of actions/instruments

The most significant barrier against the accelerated development of more advanced pre-treatment techniques is the development costs and limited market interest. Although future waste separation solutions that allow for better separation of material fractions with more specific CRM-signatures will result in improved sale values of these materials, they are expected to only partially cover the investment costs.

In the short term, only intensified use of manual labour will allow better separation and sorting of waste enabling more efficient CRM-recycling. Separation in this context means disassembling discarded products into individual components and material fractions relevant for CRM-recycling. Sorting in this context means collecting components and materials appropriate for CRM-recycling as separate fractions. This, however, is time-consuming and comes with additional treatment costs. Governmental regulations or incentives are most likely necessary for this to happen.

A more long-term solution is the development of more advanced automatic sorting and separation systems that can replace manual procedures without loss of efficiency or accuracy. This will require more advanced sensors to differentiate between specific subgroups of materials, better algorithms for making separation and sorting decisions based on collected data, and more sophisticated cybernetic and robotic solutions for executing necessary separation and sorting decisions. This is a huge undertaking, and massive R&D efforts will most likely be required for a successful result.

The Nordic region has leading scientific and engineering expertise within sensor technology and cybernetics that can be used to develop such solutions. Tomra is an example of a Nordic company that is already a supplier of automatic WEEE sorting solutions.^[131]

A national or Nordic funding scheme should be set up to develop better automatic sorting solutions that enable more efficient sorting of CRM-containing components and materials. The focus of the program should be on sorting WEEE and shredded metals. In addition, it should focus on pre-shredding techniques for scrapped vehicles that may separate CRM-containing components and materials before shredding. Manual and automatic cutting and component picking should be part of this program to develop robust, flexible, precise and safe separation and sorting mechanisms. Key technological elements expected to be a part of these automated solutions include advanced sensors and computer visions, cybernetic or robotic separation and sorting machinery, all operated by AI and deep learning algorithms. Figure 4.2 illustrates two different pretreatment regimes for metallic waste as illustrated with an EOL-vehicle. Today's dominating pretreatment practice, as illustrated in the upper scenario, is based on minimal pretreatment before shredding. The shredding process leads to the separation of main metals like iron/steel, aluminium and copper. Still, it does not differentiate between individual alloys, leading to downcycling, where the scrap metal smelted into secondary materials will most often have lower quality than the primary materials used as feedstock. In addition, the shredding process will also frequently force pieces of foreign metal into other metal fragments. This is especially problematic when copper fragments are merged with steel fragments, as copper poisons steel, but also when aluminium is merged with other metals.

Advanced identification technology would also be able to screen shredded steel fractions to find magnets or pieces of magnets that have not been sorted pre-shredding.

The second scenario, illustrated in the lower part of the figure, shows a more advanced pre-treatment regime. Here, disassembly and precise cutting replace traditional shredding, enabling the separation of individual materials and specific alloys by exploiting robotics, advanced metal-detecting sensors, deep learning algorithms and state-of-the-art cybernetic solutions to achieve smaller, more detailed and precise separation of specific CRM-containing materials that can be seen as a reverse manufacturing process.

131. <https://www.tomra.com/en/waste-metal-recycling/applications/metal-recycling/e-scrap>

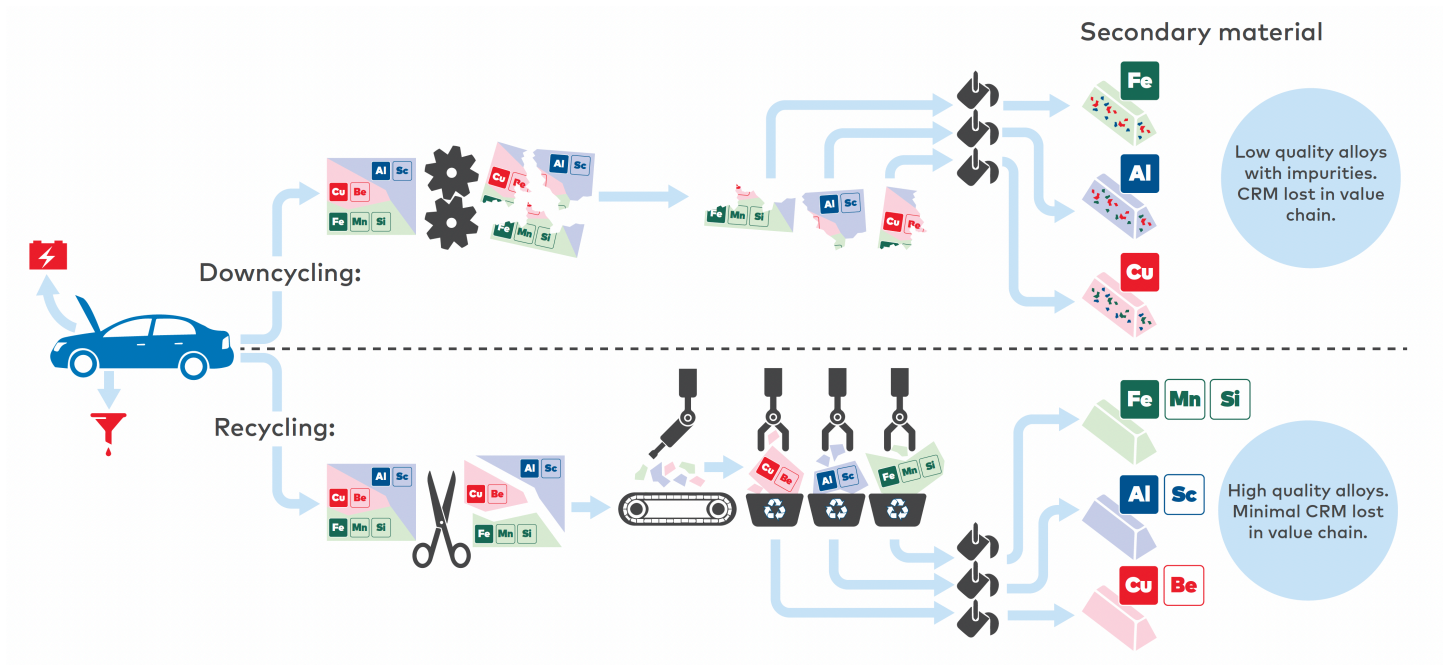


Figure 4.2 Two scenarios describing the pretreatment of metallic waste before recycling. The upper scenario describes the current dominant way scrap metal is processed through shredding which leads to poor separation of individual metals that leads to downcycling with secondary metals of lower quality than primary alternatives. This process also generates large amounts of residual waste (fines) that are made up of metal particles too small to allow further separation or recycling. The lower scenario shows an alternative pretreatment process where different metals are separated through manual cutting and then advanced separation of the same metallic materials. This allows for more effective separations of metals that can therefore be recycled more efficiently, resulting in secondary metal products of higher quality. Illustration: Bergfald Miljørådgivere.

Socio-economic impact

If a funding scheme is successful in bringing forward more advanced automatic pre-treatment solutions that allow for better sorting of CRM-material streams, this will not only contribute to reduced CRM-supply risks but also create other socio-economic benefits.

If the automatic sorting systems replace manual labour procedures, this will have the added benefit of reducing health risks associated with personnel meeting hazardous substances commonly found in WEEE and EOL-vehicles.

Successful development of next-generation waste sorting technology may create new employment opportunities and tax income. Moreover, these technologies have the potential to access markets outside of the Nordic countries where they can be exported and help increase CRM-resource efficiency.

If the funding scheme should be able to generate improved waste sorting technology solutions that lead to increased CRM-recycling, or if the market rejects the products, invested capital from the funding scheme may be partly or entirely lost.

Description and Prerequisites

A successful development of next-generation automatic waste sorting technology that allows more efficient CRM-recycling will profoundly affect three other measures discussed in this report. These are discussed in the following sections:

[4.2.2 Picking and sorting of components from circuit boards before recycling](#)

[4.2.3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding](#)

[4.2.4 Better disassembly of EE components in discarded vehicles before shredding](#)

Other variants of the measure

A funding scheme can be structured in multiple ways, either as a national initiative or a Nordic arrangement, and be dimensioned according to different levels of ambition. If the timeframe of 2030 provided by CRMA is to be the goal for the scheme, then the funding scheme will need capital in the order of millions of euros.

4.2.2 Picking and sorting of components from printed circuit boards before recycling

Circuit boards contain many material components with CRM-recycling potential, in relatively high concentrations. Today's dominant circuit board recycling solutions result in the loss of all CRMs except copper and PGM metals. While there are several plants in Europe stripping some components off the PCBs, no one has a broad approach, and the mechanical stripping technologies often end up with intermixed, destroyed or coerced components.

If circuit boards are stripped of components by gentler or even manual technologies before recycling, this will allow far more resource-efficient CRM-recycling.

The Nordic countries have established collection schemes for WEEE, which has some of Europe's highest collection rates. The Nordics also have one of the more advanced smelters for recycling of some of the CRMs. However, the sorting and pretreatment operations prior to the smelting need substantial upgrades. While a high collection rate is the foundation of a high recycling rate – they hold limited value if CRMs are lost in the subsequent sorting.

Potential for recycling of critical raw materials

There is an estimated tonnage of more than 400,000 tonnes of PCBs that are put on the market in Europe annually, of which we could expect 40–50,000 tonnes sold in the Nordics. Half of this tonnage will accumulate in homes and offices or be lost in incineration. Half of the tonnage is somehow delivered to sorting, including equipment currently outside of the EPR schemes, such as automotive equipment.

Since the first PCBs were put on the market at the end of the 60-ties, they have become increasingly advanced and complex. Currently, a broad range of PCBs will contain 70 different elements, almost the complete periodic table. Even if sorted PCBs are currently sent off for recycling, only major metals such as copper (CRM), and gold (non-CRM) are in focus. Most of the CRMs in PCBs are lost in the copper smelter and enter the slag phase.

The non-recycled elements in PCBs have now passed 6% of the total weight. This is so high a concentration that this segment of the CRM-sector needs particular attention. The overall picture for the WEEE sector is, hence, that 6% of the 40–50,000 tonnes of PCBs, or approximately 2,500 tonnes are lost.

There are many ways to approach this issue. One obvious way is reverse manufacturing. While PCBs are produced by components with very high CRM-content being attached to a board and connected via copper/gold/PGM connections, it is possible to foresee technology reversing this, picking off components the exact similar way – but reverse. However, many attempts have been made to develop robots or automatic methods to do this, but without industrial success so far. Somehow, the electronics industry in the Nordics needs to be stimulated to make ways to identify PCBs and their components fast and release (with laser or inductive heat) the connections and sort the components thereafter. If tantalum, neodymium and lithium components can be effectively separated, this may improve downstream processing significantly. The tantalum capacitors can be targeted for tantalum recycling, neodymium magnets for neodymium recycling and so on.

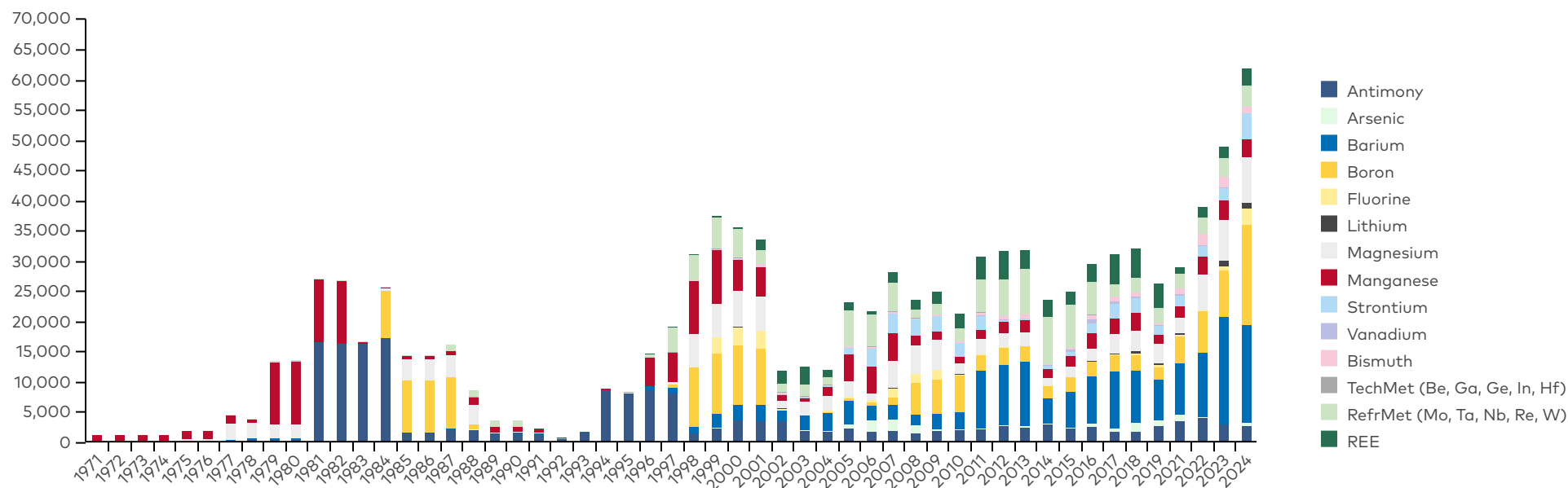


Figure 4.3 Concentration of non-recycled CRMs in PCBs since 1970, ppm. Source: Bergfald Miljørådgivere.

As electronics components historically have been high priced, there have been significant structures for reuse. This regards everything from whole boards to memory disks, chips etc. It is important to avoid disrupting ongoing reuse structures with VAT requirements or legal issues with producer guarantee requirements.

Barriers

The barriers to increased picking and sorting of PCB components are plentiful.

The legal mandate for WEEE sorting is based on overall weight, regardless of CRM or non-CRM. This gives priority to volume materials such as steel, aluminium and HIPS.

The global pricing of metals gives priority to precious metals such as gold. Indeed, even in current PCBs, the gold content represents 50% of the overall value and is by far the most important value driver.

Indeed, the CRMs we need to extract are both low-weight and low-value, so neither the current legislation nor the market is pushing for CRM-recycling.

Then, there are also other key hurdles. Increasing processing, picking, and sorting will require new technology that has yet to mature. These technologies will probably be costly to build, hence CAPEX limitations. These technologies will unavoidably also be more labour-intensive than just smashing everything in a copper smelter, thus OPEX limitations.

The product development of electronics is moving very fast, so the elemental composition and visual shape of components will change with perhaps a speed of several times a year, putting the WEEE sorting industry constantly on the back foot. In addition, there is a constant push from the industry towards using less costly metals (mainly focused on precious metals) and miniaturisation of these components.

The pricing of metals with small tonnages and few upstream stakeholders has historically been volatile, with high peaks and deep lows, making industrial investments very risky.

Consumers will expect significant discounts for reused components, reducing profitability. There will also be an inherent lack of/shorter performance guarantees for customers of reused components than virgin ones.

Possible means of actions/instruments

Economic. Establishing a deposit scheme can subsidise dismantling and recycling costs, such as contract-for-difference contracts in the Climate and Energy sector. For each element, a target value is set, for instance, at 200% of the average market price of the element in the last 10 years, and a contract-for-difference-guarantee from the deposit scheme to the recycler of a floor of that level. Giving the effect that the deposit scheme must pay the difference to the recycler if the market price falls below this level, while the recycler keeps the profit if it goes above.

Economic. Some sectors in the Nordics are exempt from or have reduced employer's tax. Companies or institutions working with WEEE for repair, reuse of WEEE components or improved recycling could have similar tax exemptions as agriculture. Removing tax burdens for green technologies has shown to be easier to implement and more durable than subsidies.

Technical. Ban using certain elements in PCBs that could be toxic to humans in contact with the material. For example, mercury, cadmium, beryllium, uranium, thorium and thallium. By removing highly toxic elements, the precaution costs are reduced.

Technical. Ban on glueing or welding of EE products. This corresponds to the Eco Design directive, which states that products shall be repairable. The same level of disassembly that makes a product repairable should also facilitate the separation of components for recycling.

Technical. Develop and mandate PCB boards of material that are easily dissolvable. Today, most boards are made of glass fibre composites, materials that, in the current recycling technologies, lock in CRMs in glassified slag. If boards are easily dissolvable in water or a suitable solvent, components would easily disentangle and separate with mechanical and optical means.

Socio-economic impact

Disassembly with component picking and sorting will require more manual labour than shredding and mechanical/chemical recycling. Many tasks are repetitive and could be relevant for persons with employment challenges. Indeed, there could be a possible overlap between social entrepreneurship and increased high-grade recycling and recovery.

Component picking is closely related to reuse, repair and refurbishment, as EEE equipment can often have a second life after replacing one or few failed components.

Increased picking of components is a recycling strategy with little or no increased consumption of energy or chemicals.

Picking plants can easily be scaled down without loss of efficiency, avoiding the need to build multi-billion-sized plants and providing industrial workplaces in smaller locations in need of such.

Selected components can become an attractive feedstock for niche chemical processing plants.

Increased picking at distributed sites might also result in earlier removal of batteries – which in turn will result in reduced frequency of fires.

Insufficient sorting and recycling of CRMs from WEEE is calculated by EY^[132] to represent a USD 57 annual loss. If this number is also applicable to the Nordics and with the high consumption and obvious losses of material – it might be, then there is a loss of USD 1 billion worth of raw material from the WEEE-sector alone in the Nordics. Improved picking might turn some of these values back into society.

Description and Prerequisites

Selecting high-value components from PCBs is as old as PCBs, and the manual reuse/recycling of components is much reduced today compared to the early years of the electronics industry – where components had a much higher value than today. While the value of components historically has been the key driver, today, scarcity of materials and recycling legislation has taken over.

Other variants of the measure

Increased component picking is a broad term covering anything from the removal of one component to a whole range of different work tasks. Indeed, all sorting of PCBs will increase circular value.

Currently, the PCBs are already sorted into different categories, mainly motivated by gold content. A sorting requirement based on CRM-content might be relevant.

132. https://www.ey.com/en_us/insights/climate-change-sustainability-services/how-circular-economy-models-can-address-global-e-waste

4.2.3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding

Shredding scrap metal and end-of-life vehicles are cost-effective treatment methods for large amounts of metal waste, but it is not very resource-efficient as they lead to insufficient separation of individual metals and loss of CRM-resources in the fine fraction that occurs during shredding of the waste. So far, no alternative fully automatic separation technique that can replace shredding and provide more efficient separation of specific metals has so far been developed. Until such processes are available, the only way to achieve higher quality separation of metals involves increased manual disassembly and cutting up of scrap metal and discarded vehicles before shredding. Although more resource-efficient, this procedure will also be more costly. Stricter requirements for such pre-treatment before shredding could improve current practice in this area.

A fleet test in Sweden a few years ago showed why this could be a viable path. At a Jönköping scrap yard, they dismantled ELVs using two parallel methods: fully manual and traditional shredding – and quantified results according to LCA standards. The shredding resulted in 73% recycling and 27% landfill, while the manual dismantling resulted in 80 % recycling, 10% incineration and 5% landfill.^[133] While these numbers speak for themselves, they cover the most important aspects; it is to expect that the manually dismantled fractions are much cleaner, as minor components such as WEEE and copper wires are not beaten into the steel and aluminium scrap pieces. Indeed, the benefits are double; it is possible to sort out all the small sensors and minor equipment pieces with high content of CRM as well as preserve the quality of base metals such as steel and aluminium.

To some degree, it is expected that the automotive recycling industry will change due to the ongoing transformation of the industry from internal combustion engines (ICE) to electric vehicles (EV). Today, ICEs are "detoxified" by removing liquids (gasoline, diesel, hydraulic fluids, etc) and starting batteries. In the future, EVs will need to have batteries removed before doing anything else. As EV engines are increasingly based on neodymium-iron-boron permanent magnets (NIB PM), it is also probable that a second life market is developing there, both for reuse in automotives of lesser brands or in the pumping market. When batteries and engines are removed, the remaining EVs make little sense to shred from a technical point of view.

Substantial work has been carried out to improve the recycling of materials from shredder residues – the materials left from shredded scrap metal after iron and aluminium has been sorted. It hasn't proven easy to achieve high circularity for this fraction, which is understandable as all materials have been banged together.

Potential for recycling of critical raw materials

Currently, the recycling of CRMs from scrapped vehicles is very low, except for copper wiring and aluminium components. Larger WEEE components are sometimes, but not always, dismantled, mainly due to gold values. With manual dismantling, the recycling rate of the minor CRMs might go from close to zero to significant.

Based on the available statistics of CRM in shredder residues, the neodymium content alone represents a loss of more than 100 tons per year. Additionally, most neodymium and other magnet metals will follow the magnetic iron fraction to steel recycling. In both cases, the neodymium is lost if not sorted out before shredding.

133. Gradin et al. Investigating improved vehicle dismantling and fragmentation technology. Journal of Cleaner Production. 2013.

Manufacturers of automotive parts in the Nordics that receive sorted components with identical alloy composition as new components should receive a small subsidy from the automotive deposit to recycle the material back into the same material level, hence avoiding downcycling. SSAB steel rolling mills could receive car parts such as doors directly and avoid contaminating these components with CRMs such as copper and neodymium. Similar examples are for the aluminium bumper industry – if aluminium bumpers go directly from dismantling to the bumper factories (of which the Nordics have several), downcycling of alloying elements is avoided.

Barriers

The critical barrier is cost. Using manual labour is costly in the Nordics. It is unavoidable that labour costs and, hence, OPEX will be significantly higher than traditional shredding. However, capital costs will largely be avoided, as no heavy machinery is needed. Indeed, manual dismantling makes it possible to have many distributed recycling hubs instead of a handful of large shredding facilities. A socioeconomic evaluation on which dismantling system provides the best solutions should be made and could be a part of a national CRM-policy.

Original equipment manufacturer (OEM) requirements on recycled content are sometimes a problem. Due to the lower quality of many recycled metal fractions, OEMs have understandable limitations and documentation requirements. Closing the circle on components might mitigate this barrier.

Competence will be a challenge. Thousands of persons will need to be trained to recognise, properly dismantle and sort materials from thousands of different models of vehicles.

Industrial protests from the scrapping industry will be a hurdle.^[134] The transformation of an industry also means that the current position of the prominent participants is threatened. Increased requirements for manual dismantling of components as part of the EU Green Deal (in parallel to, but not a part of, CRMA) has resulted in strong wording and protests from the associations of the shredder industry.^[135]

Possible means of actions/instruments

Tightening of regulations. Landfills in Finland and Norway, perhaps also in other Nordic countries, have been able to classify landfilling of shredder fluff and shredded tyres as "recycling" based on an argument on the need for drainage in landfills for inorganic materials. Indeed, while landfilling is sometimes needed, the term "recycling" should not be inflated.

Tightening of classification should be considered. If extruded and rolled aluminium components are recycled as casting alloys, this should be considered downcycling.

Increased deposits. All the Nordic countries have deposits on vehicles to finance the delivery, transport and detoxification of scrapped vehicles. It should be considered that these should be increased significantly to cover increased labour costs in the dismantling.

Socio-economic impact

Increased manual dismantling can utilise the work of a low-skilled labour force. The threshold for establishing a dismantling hub will be low and could henceforth make distributed workplaces possible. An avoidance of monopolies and oligopolies in the recycling industry will be mitigated. Increased purity of base metal fractions will also avoid the need for virgin material for dilution and, hence, increase real circularity.

134. https://www.acea.auto/files/ELVR_joint_statement_EuRIC_ACEA_CLEPA.pdf

135. <https://www.euwid-recycling.com/news/business/euric-and-automotive-associations-against-mandatory-dismantling-of-certain-end-of-life-vehicle-parts/>

Description and Prerequisites

This measure interfaces with several other measures described in this chapter. Manual dismantling and cutting should be replaced by automatic procedures that can obtain similar quality separation for both economic and safety reasons. The development of such technologies could be encouraged through economic support schemes described under section 4.2.1 R&D programmes to develop better sorting technology. The measure may overlap with section 4.2.3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding. The resulting output of the measure will be beneficial for the successful implementation of measures described in the sections:

[4.3.2 Develop business models that enable the establishment of networks of Nordic steelworks that more clearly specialise in the recycling of specific alloy qualities](#)

and

[4.3.3 Develop business models that enable the establishment of networks of Nordic secondary aluminium works specialising in the recycling of specific alloy grades as it will make it possible to deliver larger amounts of scrap metal for high-quality niche recycling.](#)

Other variants of the measure

Current legislation mandates the removal of liquids and batteries before shredding. This mandate is based on safety and protection against pollution. The aim of CRMA of security of supply needs to be included. A variant would also mandate the removal of all WEEE (including all wiring) and components of a specific size of magnesium alloys (seat frames, steering column, etc.).

A more aggressive variant is to mandate manual dismantling of all other larger equipment, such as tractors, bikes, e-bikes, buses, trailers, aggregates etc.

4.2.4 Disassembly of EEE components in discarded vehicles before shredding

Vehicles increasingly contain EE components, which are placed in many different and often inaccessible locations in the vehicles. When shredding scrapped vehicles, the main WEEE components are mainly sorted post shredding, and most of the minor WEEE components are either smashed into the steel and aluminium parts – or end up entangled in the fluff or fines fraction which are landfilled or incinerated and therefore lost for recycling purposes.

The EE components often consist of small electric motors based on neodymium magnets covered in copper wiring, tiny engines moving seats back and forth, window heists, windshield wipers, fluid pumps and others. There may be 50 small motors in a vehicle. A modern car also has tens, if not hundreds, of sensors monitoring tyre pressure, humidity, temperature and cameras in both directions. Almost all these tiny items represent large amounts of CRMs, but each of them is tiny, laborious to dismantle and hence mainly lost today.

All electronic equipment other than vehicles are, with a few exceptions,^[136] mandated to collect and sort for recycling the WEEE components. Indeed, including scrapped vehicles in the European legislation for WEEE might be one of the large low-hanging fruits for CRMA compliance.

136. Disclaimer: also airplanes, defence equipment and certain medical equipment is in general exempt from the legislation.

Potential for recycling of critical raw materials

The number of electronic components in vehicles is complex and difficult to estimate, but all references indicate a strong growing trend as infotainment screens, sensors, cameras and convenience motors increase in prevalence. As for fractions with high CRM-content, the volume should be thousands of tonnes on a Nordic level. The high CRM-content in shredder fluff and shredder fines confirms this.^[137]

Although the current WEEE EPR recycling value chain has its limitations and shortfalls, it will be able to accept added volumes from the automotive sector and provide better recycling options.

Barriers

Cost and competence will be a barrier, as manual dismantling of WEEE will require several minutes of labour per scrapped vehicle.

Possible means of actions/instruments

The exception of vehicles from the WEEE directive should be removed, such that the automotive sector will have equal regulations as most other industries. Included in this should be a membership in an EPR scheme and a separate deposit on sales of new cars to cover the cost of manual dismantling, like the deposit tariffs of all other EE equipment.

Efforts should also be put into developing improved technology for locating small WEEE components in vehicles, as they are often well hidden.

Socio-economic impact

Increased manual dismantling might need more skilled recruited labour with limited job opportunities. An increased volume of WEEE coming into the value stream will make all downstream processing steps less costly and more profitable.

Description and Prerequisites

This measure interfaces with several other measures described in this chapter. Manual removal of EE-components from scrapped cars before shredding is today the only available technique for high-quality sorting. It should, however, be replaced by automatic procedures that can obtain similar quality separation for both economic and safety reasons. The development of such technologies could be encouraged through economic support schemes described under [section 4.2.1](#) R&D programmes to develop better sorting technology. The measure may overlap with [section 4.2.3](#) More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding. The resulting output can serve as feedstock for processes developed under [section 4.3.5](#). Development of recycling process for circuit boards and other EEE waste that recovers more CRMs

Other variants of the measure

One less material-efficient measure is to mandate strict post-shredding WEEE sorting.

A hybrid version would mandate the dismantling of infotainment screens and other major electronic components from the dashboard but leave the many small motors and sensors in the vehicle.

137. <https://www.norden.org/en/publication/recycling-critical-raw-materials-nordics>

4.2.5 Organised emptying and dismantling of hand-held fire extinguishers

Hand-held fire extinguishers are ubiquitous in the Nordics, with more than one million sold yearly. While the extinguishers come in different sizes, the dominating size weights about 10 kg, of which 6 kg is MAP, monoammonium phosphate.^[138] In addition, the units consist of about 3–4 kg of alloyed steel or aluminium and a coupling of 0.4–0.5 kg of brass – a copper alloy. The main market is still dominated by steel cylinders, but aluminium cylinders are replacing steel to some degree. As the extinguishers get old, they lose efficiency and need either service or a full replacement, as almost no fire extinguishers are actually used for their intended purpose. A fire extinguisher that is not able to extinguish fires should be removed to avoid false sense of safety.

Properly dismantled, almost all of the materials in old fire extinguishers can be recycled with a high degree of recycling back to a similar product level.^[139]

While at least 60% of new fire extinguishers come from China, the replacement and recycling of old ones are a problem. In the Nordic region, up to one million old and inefficient hand fire extinguishers are either accumulated in basements and garages, thrown into residual waste or dumped in nature every year. It is not uncommon to see smaller scrap yards emptying old units to then sell the metal as scrap steel. Such disposal in nature and other unauthorized use of the material is highly problematic,^[140] while all kinds of recycling, including downcycling of downgraded material to other uses of MAP have a very good environmental profile.^[141]

Improper or complete lack of recycling options has, over the years, resulted in a loss of phosphate and less resource-efficient metal recycling, as the attached brass coupling is often not removed before the steel container is recycled. By direct recycling of the steel without mechanical removal of the brass coupling, the steel becomes contaminated.^[142] Also, phosphorous is the worst contaminant in steel, with strict requirements to avoid brittleness. If old fire extinguishers are not suitable for reuse/refill, they need to be properly cleaned before they are sent to steel recycling to avoid phosphorous contamination.

The Nordic region already has recycling facilities that handle many old units.^[143] With a simple conversion, these can have increased access to raw materials and a rapid increase in recycling/reduced emissions into nature.

Potential for recycling of critical raw materials

As the standard model dominates the handheld fire extinguisher market, we estimate a recycling potential of 6,000 tonnes of MAP, at a quality mainly suitable for direct reuse. Tests show that the powder maintains quality over time and can be reused.^[144] In addition, about 4–500 tonnes of brass with a content of appr 3–400 tonnes of copper and about 3–4000 tonnes of aluminium or non-CRM-steel alloy will be reused or recycled.

138. There are also fire extinguishers based on other technology platforms, but they represent very small market shares.

139. Urquiga et al. The Recycling of Fire Extinguisher; First Step Toward a Circular Economy. Proceedings of the International Conference on Industrial Engineering and Operations Management. 2019.

140. Jeong et al. Assessment of Hazard and Recycling for Discarded Agent in Powder Fire Extinguisher. Journal of Korea Society of Waste Management. 2015.

141. Gelsomino et al. Exhausted fire-extinguishing powders: A potential source of mineral nutrients for reuse and valorisation in compost enrichment for soilless cultivation. Science of the Total Environment. 2024.

142. Bergfald Miljørådgivere. Komparativ livsløpsvurdering - potensiale for redusert CO₂-utslipp ved økt gjenbruk av brannslukkere. Konfidensiell kunderapport. 2021.

143. <https://miljonorge.no/>

144. Kim et al. Performance of Recycled Fire-Extinguishing Agents in Terms of Fire-Fighting Performance Management. Fire Science and Engineering. 2020.

Barriers

The main barrier is the lack of infrastructure for receiving, testing, refurbishing and emptying/refilling the extinguishers. Capacity exists, but it needs to be expanded.

Millions of units are standing idle in homes, cabins, offices and workplaces without pressure, useless in the event of any fire. Stricter routines should be implemented in all consumers to check the pressure and condition of units and return old and useless units for recovery.^[145]

Importers and producers of fire extinguishers might lobby against any recycling incentives.

Possible means of actions

The most efficient instrument would be establishing a deposit scheme of, for example, DKK 1,000 per fire extinguisher. This will be able to finance a scheme where discarded fire extinguishers are emptied in a controlled manner, MAP can be recycled, and the container can either be reused or dismantled for high-quality recycling of steel and brass. With a high deposit, the threshold for exchanging an old unit with a new one becomes much more attractive.

When sufficient recycling capacity is available, new information campaigns should be rolled out in all Nordic countries to ensure that all homes, cabins and workplaces that need a handheld fire extinguisher have one and that it is checked and recycled. Governments in all the Nordic countries have experience with similar fire safety campaigns from before.

Socio-economic impact

An improved system for checking and recovering fire extinguishers will also improve preparedness in case of fires. Indeed, both life and property might be saved if the routines of checking these units are improved.

Recycling and refurbishing fire extinguishers will provide industrial workplaces that can be placed in logistically sound societies. These plants do not need to be very large nor are they very capital-intensive.

Description and Prerequisites

Removal of MAP and dismantling and cleaning of the metal containers must, currently, be done manually, as no automatic system has so far been developed to handle this operation. Developing such an automated system could potentially be encouraged through economic support schemes, described in [section 4.2.1](#) R&D program to develop better sorting technology.

Other variants of the measure

Tariff on import of fire extinguishers from outside of Europe and/or on units based on virgin material.

Substitution of MAP with other powders. This is probably not an attractive solution due to possible reduced firefighting capacity.

145. Son et al. An Experiment on Apparent Specific Gravity and Settleable Degree of Fire Extinguishing Agent according to Durable Years of Regional Powder Extinguisher. International Journal of Membrane Science and Technology. 2023.

4.2.6 Assess the possibility of incineration of selected waste streams in dedicated waste incineration plants to increase the CRM-concentrations in the ash residues.

Mixed waste contains countless types of discarded products and materials, some of which contain CRMs. In addition to ordinary mixed waste, discarded CRM-rich products like electronics, batteries and metal scrap that are also collected separately are commonly found in mixed waste due to poor sorting. The most common end treatments for mixed waste are incineration and landfilling. All CRMs in the waste being incinerated are found either in the bottom ash or fly ash afterwards albeit normally at concentrations that make recovery difficult.

Incineration ashes serve as a sink where CRMs from many diffuse waste streams that cannot be easily collected separately end up. Although the concentrations are low, due to the large volume of incineration ashes generated each year, the total amount of CRMs found in this ash is significant. In the Nordic countries, around 16 million tons of waste is incinerated each year giving rise to about 2.5 million tons of bottom ash and 0.5 million tons of fly ash.^[146] When ashes from incineration of biomass are added the Nordic ash volume totals around 6 million tons.

Bottom ash is made up of large, heavy and non-volatile ash particles that are collected from the bottom of the incineration chamber. Compared to fly ash bottom ash often contains up-concentrated levels of vanadium and silica. Fly ash is smaller, lighter and more volatile ash particles that follow flue gas and are collected as part of the flue gas treatment. Compared to bottom ash fly ash typically contains up-concentrated levels of arsenic, lithium and antimony.^[147]

Incineration of mixed waste means that waste types that contain both high and low levels of CRMs are incinerated together. This practice results in diluted CRM concentrations in the ashes compared to if the CRM-rich waste fraction that was incinerated separately. For this reason, the possibility of selective incineration of only CRM-rich waste fractions should be considered, as this may lead to higher CRM-concentrations in the resulting ash that may make CRM-recycling more favourable. Ashes typically contain around 1% of CRMs when aluminium, magnesium and silicon are excluded. If CRM-rich waste in the mixed waste stream were incinerated separately, one would expect the CRM-concentrations in the resulting ash to increase significantly. CRM-rich waste types that should be considered for selective incineration include shredder residue, tyres, textiles with flame retardants, and toys, in addition to batteries and WEEE that are targeted for incineration for safety reasons together with CRM-rich industrial waste.

Potential for recycling of critical raw materials

Nordic incineration ash contains thousands of tons of CRM, albeit in low concentrations. If these CRMs could be concentrated to levels that allow for cost-efficient recovery, recycling of only a fraction of the Nordic incineration ashes could provide a significant output of secondary CRMs, including copper, nickel, lithium, gallium, germanium and REE.

Barriers and possible means of actions/instruments

There are both technical and economic barriers that need to be overcome for large-scale CRM-recycling from incineration ashes to become a reality.

Selective incineration of CRM-rich waste could either be performed in a new incineration plant designed for this purpose, or in a conventional incineration plant rededicated for this purpose. If a specialized Nordic incineration plant is built for this purpose this will come with a significant

146. Waste incineration in the Nordic countries, Nordic Council of Ministers 2024.

147. Metode for enklere fastsettelse av FA-grenser for utvalgte avfallsfraksjoner, Avfall Norge rapport. 2019.

CAPEX. In addition, there is already a Nordic waste incineration overcapacity that could be worsened by an additional plant operating in the same market.

It may, therefore, be more cost-efficient to rededicate an existing plant to burn only CRM-rich waste. However, most existing waste incineration plants are designed for a mixture of waste streams, and changing this mixture by excluding CRM-poor waste may cause challenges both in the incineration chamber, where temperature regulation may become an issue and later when cleaning the flue gases that may contain higher concentrations of pollutants than what the treatment system is designed to deal with.

Existing Nordic waste logistics may also be disrupted by redirection of large waste volumes in ways that may negatively affect the utilisation of available incineration capacity and raise operational costs due to longer transport distances and longer temporary storage requirements.

An assessment of the possibility of incineration of selected waste streams in a dedicated waste incineration plant should, therefore, not only consider the potential CRM-benefits, but also issues regarding costs, potential market disruptions and possible added pollution risks associated with such a practice.

Socio-economic impact

The socio-economic benefit of incineration of CRM-rich waste in a dedicated incineration plant will mainly come from the increased recovery of CRMs. Such a solution represents an opportunity to create a circular material loop for CRMs that are part of waste streams that would otherwise be difficult to recover,

The cost of doing an assessment of the possibility of incineration of selected waste streams in a dedicated waste incineration plant to increase the concentration of CRM levels in the ash residues will obviously be limited. If this process leads to full implementation this will come with significant costs.

Regardless of whether selective incineration of CRM-rich waste takes place in an existing or newly built facility, such an operation will come with significant operational costs. If a dedicated Nordic incineration plant is built, this will also come with a CAPEX. CAPEX for a typical 50,000-tonne MSW incineration will normally be around DKK 600 million.^[148]

Description and Prerequisites

Assessing the feasibility of the mono-incineration of CRM-rich waste should be seen in relation to the measure described under [section 4.3.7](#). The development of new technology for the extraction of CRMs from ash will obviously become more attractive if ash with higher CRM-concentrations becomes available as a feedstock for this process. At the same time, a scenario where the mono-incineration of CRM-rich waste is shown to be unrealistic should not disincentivise technology projects for CRM-extraction from ordinary ashes.

Other variants of the measure

Better sorting of mixed waste could extract CRM-rich waste directly, like WEEE and batteries that have been missorted.

148. <https://wteinternational.com/news/cost-of-incineration-plant/>

4.2.7 Analyse wastewater from geothermal power stations for anhydrous CRMs

Water from geothermal facilities in Iceland contains elevated levels of inorganic elements, including CRMs. The potential for extraction of CRMs, which include lithium and boron, from these facilities, should, therefore, be assessed.

The occurrences in Iceland are unique in a European context in its abundance, but not unique in relevance. Indeed, a lithium extraction plant based on geothermal production water has operated in California for many years, and another is under construction in Germany. Several projects are planned globally.

Iceland has many geothermal energy plants producing both electrical power and distributed hot water. Some of the power plants reinject heated water after power production, but it may be estimated that approximately 150 million tonnes of brines with varying concentrations of metal ions are emitted as a waste fraction to the environment.

In both Iceland and other countries, such geothermal effluents have proven rich in CRMs such as lithium or boron possibly other CRMs. While many of the analyses observed show medium to low concentrations, there are also some high-concentration sources. No individual assessment of each geothermal resource or power plant has been made in this report. An estimate has, however, been done based on aggregated figures for discharge volumes combined with average concentrations of elements. As a basis for this estimate, published data from geothermal resources such as Seltjarnarnes,^[149] Keldunes,^[150] Hofstadir,^[151] Reykjanes^[152] and power plants such as Hellisheidi,^[153] Nesjavellir,^[154] Reykjanes,^[155] Theistareykir,^[156] Krafla^[157] and Svartsengi^[158] have been utilized.

Potential for recycling of critical raw materials

While the concentration of the CRMs is low in the brine, the consistency of production and the high temperature and pressure of the brine make extraction easier and create a recovery potential.

Based on high-level average numbers, it seems the emitted volumes of Icelandic geothermal brines contain 700 tonnes of lithium, sufficient for 70,000 electric vehicle batteries. The level of boron is similar and represents one of the few boron sources in Europe.

It will, of course, be optimal to install a lithium extraction unit on the brine with the highest concentrations, regardless of whether this brine is reinjected or emitted.

Tests and case studies have already been made, showing that the brine from the Nasjavelli power plant could produce more than 1 tonne of lithium daily.

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149. Kristmannsdóttir, H. et al. The development of the Seltjarnarnes geothermal field, SW Iceland during thirty years production. Proceedings World Geothermal Congress. 2000
150. Kristmannsdóttir, H. et al. Online Monitoring of Corrosion in Slightly Saline Geothermal Water in Iceland. GRC Transactions, Vol. 36. 2012
151. Kristmannsdóttir, H. et al. An anomalous thermal water from Hofstadir western Iceland: Evidence for past CO₂ flushing. Applied Geochemistry. 2012.
152. Olafsson et al. Geochemical studies on the thermal brine from Reykjanes (Iceland). Chemical Geology 1978.
153. Stefansson et al. The geochemistry and sequestration of H₂S into the geothermal system at Hellisheidi, Iceland. The geochemistry and sequestration of H₂S into the geothermal system at Hellisheidi, Iceland. 2011.
154. <https://thegreenprogram.com/capstone/lithium-extraction-from-icelandic-geothermal-brine/>
155. Sveinbjörnsdóttir, E.A. Composition of geothermal minerals from saline and dilute fluids Krafla and Reykjanes, Iceland. Lithos. 1992.
156. Oskarsson et al. The Theistareykir geothermal field, NE Iceland: fluid chemistry and production properties. Procedia Earth and Planetary Science. December 2013
157. Saby et al. The behaviour of metals in deep fluids of NE Iceland. Nature. 2022.
158. Ragnarsdóttir et al. Description and interpretation of the composition of fluid and alteration mineralogy in the geothermal system, at Svartsengi, Iceland. *Geochimica et Cosmochimica Acta*. 1984.

Barriers

It may be difficult to achieve an economically sustainable business model for such a project due to the low prices of lithium, as many new sources come to market

There may also be insufficient technologies for separation from brines and conflict with energy efficiency goals.

Lack of overview of process parameters increasing/reducing concentrations and lack of risk capital for unconventional mineral sources may also represent obstacles that need to be overcome,

Possible means of actions/instruments

Such a project could potentially receive support and offtake agreements with major European battery manufacturers. Establishment of risk capital instruments (equity, soft loans^[159] etc.) and R&D on improved recovery technologies represent other means through which a project could be realised.

Socio-economic impact

CRMs extracted from wastewater from geothermal power stations could potentially supply additional CRMs to the European market with a very low environmental footprint. Such an operation could also provide additional jobs and export income for Iceland.

Investments in CRM-extraction will generate a new source of income for power companies, making them more resilient towards changing power prices and, as such, more attractive for investments – which again might spur more geothermal power development. This is illustrated by a simplified overview of the power market in Iceland in the period 2010–2022 where geothermal power production is multiplied by wholesale power prices (not including heating tariffs) and combined with average values for the content of some minerals. It is important to stress that the different sources around Iceland vary significantly, so this image shall be used as an illustration only and not as representative of any plant potential. That said, the illustration shows an undeveloped potential for new supply lines for CRMs from existing industrial infrastructure.

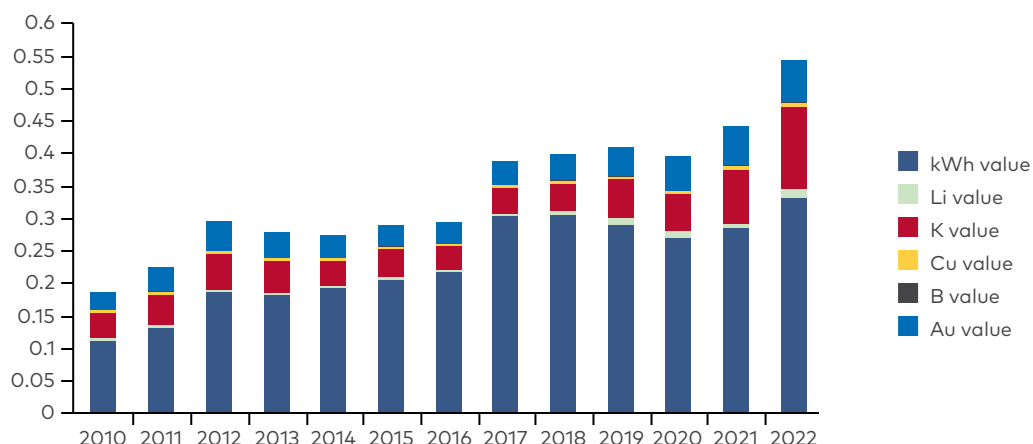


Figure 4.4 Possible added value to geothermal plants. Source: Bergfald Miljørådgivere.

159. Soft loans are loans that comes with a below-market rate of interest and sometimes also other concessions. Such loans are also known as soft financing and is commonly provided by governments to projects that are considered of strategic importance.

Description and Prerequisites

The development of extraction technology to recover CRMs from wastewater from geothermal power plants could potentially receive support from economic support schemes described in [section 4.3.1](#).

Other variants of the measure

Iceland has investigated some sources of geothermal energy that have not been developed partly due to high concentrations of minerals in water. With minerals as the main objective and energy as a secondary byproduct, some hybrid projects might be developed.

Some ashes contain some of the same elements. These ashes could be added to geothermal brines to increase concentrations and extract tonnage.

4.3 Better recycling solutions

Collection and sorting of waste has little meaning if no recycling operation is available as an off taker. The Nordic countries already have industries that could play a bigger role in future CRM-recycling either by expanding and improving existing recycling operations or by leading or supporting the establishment of new ones.

4.3.1 R&D program for the development of new or more efficient CRM-recycling processes.

Recycling critical raw materials from many waste streams is so far impossible as no technology has yet been developed that allows this. For this reason, there is a need for a massive R&D effort if value chains for secondary production are to be established for all CRMs. Moreover, the recycling efficiency of many existing CRM-recycling processes is very low. For example, today's recycling of circuit boards results in copper and gold being recycled while tens of other important CRMs, including tantalum, gallium, germanium and REEs are lost in the slag. Discarded batteries, ammunition residues, and fines from shredding scrap metal and WEEE are examples of other CRM-containing waste streams where there is a need for the development of new and better recycling processes.

The Nordic countries have significant primary production of CRMs such as aluminium, copper, nickel, silicon, manganese, PGM and REE, and they have associated technological expertise that can be utilized when establishing value chains for secondary production of the same materials.

In universities and research institutions around the Nordics, tens of new recycling technologies are tested and matured at the moment, supported by either national or EU grants – or both. Some of these technologies are new to the world, while others are innovative concepts that have been used for other purposes or industries, and that could be adapted to CRM recycling. This could include, for example, supercritical extraction,^[160] laser excitation,^[161] or using bacteria, algae or fungi to release^[162] or bind^[163] CRM elements. As many traditional pyrometallurgical, mechanical and hydrometallurgical processes and magnetic, gravimetric or density-based technologies for

160. Zhu et al. Supercritical carbon dioxide/nitrogen/air extraction with multistage stripping enables selective recovery of rare earth elements from coal fly ashes. RSC Sustainability. 2023.

161. Zare, R. Laser Separation of Isotopes. Scientific American. 1977

162. Isildar et al. Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) – A review. Journal of Hazardous Materials. 2019.

163. Ordóñez et al. Biosorption of Heavy Metals with Algae: Critical Review of Its Application in Real Effluents. Sustainability. 2023.

several waste streams have reached technical maturity and only incremental progress might be expected, the new technologies in their industrial infancy might be the workhorses for the next generation of separation plants. This will only be possible if research institutions with good ideas get funding to test, and if companies wanting to try novel technologies get risk mitigation through Government funding.

The current dominating recycling technologies tend to end up with residues which are hard to process further. From pyrometallurgy, the residues with elevated CRM-levels end up in glassified slags, and from hydrometallurgy, the residues end up in complex precipitates. One key objective when developing new technologies should be that the processed material is not impossible to process further with other technologies.

Potential for recycling of critical raw materials

Development, maturing, and industrial implementation of new technologies take decades and involve huge financial risks for the companies involved. However, when technologies succeed, the gain can be phenomenal. All the limitations currently seen in existing technologies can, in principle, be overcome with new and improved technologies.

Barriers

Insufficient and short-lived funding is the main limitation for the development of new technologies for CRM-recycling. A central observation in Europe and the Nordic is that it seems to be relatively easy access to public funding for basic science and very early tests, i.e. projects in the TRL 1–3 stage. However, all technologies need to be upscaled, matured and tested over time in realistic conditions. The long and costly path from a science level of TRL1–3 to an industrial investment level of TRL 7–8 has insufficient funding programs in all the Nordic countries.

Competence is an increasing limitation. While China, India and many other non-OECD countries prioritize STEM education and continuously increase the number of PhDs and full-time R&D personnel^[164] and publications they produce, Europe has fallen behind in this regard. In the last two decades, the STEM part of higher education in the EU has fallen from 17% to 14%, with a consistent falling trend over time. If future recycling industry shall be successfully developed in Europe, STEM education needs to be strengthened.

Possible means of actions/instruments

Larger and more predictable funding is crucial for the accelerated development of better CRM-recycling technologies spearheaded by the Nordic countries. At any TRL-level, funding should be given according to an agreed progress plan describing a set of relevant milestones. If these milestones are met, further funding should be automatic and not based on new applications and evaluation boards that quite often are diverging attention and slowing progress.

CAPEX-intense funding for high TRL programs can be provided as long-term soft loans without collateral, to be paid back if the technology becomes successful and is industrialised. Having more funding as loans and not grants will, on one hand, increase public acceptance of high-level spending – and, on the other hand, condition researchers towards commercial thinking.

Specific R&D funding should also target SMEs, as smaller companies have proven more important when it comes to introducing disruptive technologies, compared to large corporations that more often focus on incremental improvements.^[165]

164. Niancai et al. Education in China and the World. Springer. 2024.

165. European Parliamentary Research Service. The role of research and innovation in ensuring a safe and sustainable supply of critical raw materials in the EU. 2024.

Increased funding for post-doc and research positions in universities and research institutions is also important for ensuring competent people who can make a difference keep working.

There should also be an evaluation of whether the Nordic structure of R&D funding has a higher or lower success rate compared to the EU Horizon funding. If the Nordic models are more efficient in creating actual production plants – many of the Nordic countries should seek to export the model.

Socio-economic impact

Research has shown a clear correlation between changes in STEM education and employment in society and GDP. While the coefficient can vary over time and between countries, a typical factor is that a 1% change in STEM education and employment will result in a 2.4% change in GDP.^[166] While the main purpose of increased R&D programmes for CRM-recycling is the CRM, it is also fair to consider that these investments into people and competence are also highly profitable for society.

Description and Prerequisites

An economic support scheme for R&D efforts towards better CRM-recycling technologies could be important for the successful implementation of several other measures discussed in this chapter, including:

[4.3.2 Develop business models that enable the establishment of networks of Nordic steelworks that more clearly specialise in the recycling of specific alloy qualities](#)

[4.3.3 Develop business models that enable the establishment of networks of Nordic secondary aluminium works specialising in the recycling of specific alloy grades](#)

[4.3.4 Establishment of a Nordic recycling plant for gallium from industrial wastes from zinc and aluminium](#)

[4.3.5 Development of recycling process for circuit boards and other EE waste that recovers more CRMs](#)

[4.3.6 Develop business models that enable the restart of closed CRM-recycling facilities](#)

[4.3.7 Development of technology for the extraction of CRMs from ash residues](#)

Other variants of the measure

Generally increased funding to science and research without a particular focus on CRM will also partly benefit CRM-recycling, but with less obvious results.

Increased incentives for the recycling industry, such as double tax deductions for funds used for innovation in CRM-recycling.

166. Croak, M. The Effects of STEM Education on Economic Growth. 2018.

4.3.2 Develop business models that allows the establishment of networks of Nordic steelworks that more clearly specialise in the recycling of specific alloy qualities

Steel is an iron alloy that contains some carbon and often several additional and modifying metals. Steel alloy components commonly used include manganese, nickel, vanadium, niobium and silicon. Primary steel alloys are prepared from iron ore through a complex and energy-intensive multistep process where ore is reduced to metallic iron.

Secondary steel is produced by re-smelting scrap steel into new material without any chemical reduction process. The market for steel scrap differs from virgin steel by feedstock limitations. While primary steel can easily establish new iron ore mines and reduce smelters, it is not possible to increase the tonnage of steel scrap. Indeed, almost all iron and steel that end up as waste will eventually also end up in a recyclable fraction. Diversion of exports or increased imports is the only realistic way of significantly influencing available volumes. This issue, even if mundane, is of critical importance to Europe, as the energy crisis of the latter years has prompted a fast transition of traditional iron ore blast furnace pig iron production into several investments in scrap-based EAF plants. This means that many more EAFs are established to compete over the same amount of scrap iron – and with less pig iron available to dilute and balance out contaminants and alloying elements.^[167] Scrap iron should, therefore, no longer be merged and mixed into one fraction.

Indeed, the uncoordinated restructuring of the European steel industry, with many stakeholders chasing the same feedstock, has prompted a scrap problem. The only way to balance out these fast changes in the industrial infrastructure is to dramatically increase scrap sorting such that the different EAFs can avoid downcycling or purchasing imported CRM-based alloying elements.

Most steel works and iron foundries in the Nordic countries work within a rather limited range of alloy specifications for each plant, and most of them keep to these alloys for years and decades. Indeed, while output is rather fixed, it is the input feedstock where differences occur, and where improved systems and models need to be developed. Even if there are many companies working in the iron and steel processing industry in the Nordics, they each have their niches and competition amongst these companies is not that prevalent.

Many CRMs are used as steel alloying elements; for example, nickel, vanadium and niobium can be found in different concentrations in steel scrap. Before re-smelting, scrap steel is sorted into separate quality classes. This aims to optimise the existing content of alloy components other than iron and limits the need to add costly alloy materials to the secondary steel product. An additional priority when pre-sorting steel scrap before recycling is to limit the introduction of copper into the secondary steel product, which becomes a pollutant that lowers the final product quality. Because different sorting processes are less than perfect, significant amounts of CRM-alloys will end up in secondary steel materials where they serve no purpose and will, sometimes, lower the material quality instead of being recycled in secondary steel products where they are needed as part of the product recipe.

Better pre-sorting of scrap steel into specific alloy qualities may ensure a higher recycling rate of CRM-alloy components,^[168] and limit the production of secondary steel products with lower quality due to unwanted pollutants. Better pre-sorting techniques are available, but they are often not cost-effective and, therefore, not applied.

167. <https://gmkn.center/en/news/scrap-shortage-situation-in-europe-will-get-worse-federacciai/>
168. Quintè, S. Optimization of alloys recovery in steel scrap sorting. KTH. 2023.

If a mixture of scrap steel alloys containing different CRMs is mixed in the same furnace, the resulting secondary steel product will contain a blended mixture of CRMs at diluted concentrations compared to their original recipe.

It is fair to say that despite the best intentions of the recycling industry, today's steel recycling is a structural downcycling. High alloyed steel scrap components are mixed with lower alloyed components and then either diluted with pig iron or corrected with virgin alloying material. In a period where there is material growth, and new material is always needed, this can work well, but in a circular economy, this will not be possible. A recycling rate of 50% will effectively mean that any product is used twice; first for its primary use, then for a secondary (lesser) use and then lost or unusable. The current global situation is actually less than that, with approximately 650 Mt scrap used in total steel production of more than 2 billion tonnes – one-third is scrap-based.

Steel scrap from recycling of WEEE appliances (mainly major items such as refrigerators, freezers etc.) consists of rolled steel of high and predictable quality. Most of the producers of such appliances have ended up using the same and few alloys. As the tonnage is substantial, we would expect steel from refrigerators alone to be about 20,000 tonnes in the Nordics every year. In the current WEEE processing plants, refrigerators are manually depolluted and then shredded and sorted. For example, the shredding currently performed will unavoidably cause a contamination with copper. Due to the copper content, the steel has a very low value in the European market, and these fractions of originally good steel are henceforth exported to India^[169] to use in variants of stainless steel where copper is accepted. If copper (and other contaminants) had been properly removed, these fractions could have been recycled back to the same rolled steel quality as it originally was in a closed circle.

In rolled steels, copper is typically limited to less than 0.1%. With hammer milling of appliances and vehicles, it is basically not possible to avoid hammering in small pieces of copper wires, as well as small brass screws and joints etc. The copper is possible to remove metallurgically later on but at significant cost both in terms of material loss and energy and waste production.^[170]

Better sorting of steel scrap before re-smelting in dedicated furnaces for specific alloy qualities will allow a higher CRM-resource efficiency in future generations of steel products.

Nickel is one of the steel alloying elements that have a prominent place on the CRM list. While nickel is mainly talked about as crucial for lithium batteries and advanced stainless-steel alloys – the big bulk of nickel consumption is as a minor alloying element in millions of tons of steel. In a German test publicized earlier this year,^[171] the steel fraction of 100 refrigerators was separated out, processed and recycled. A detailed elemental analysis showed 0.3% nickel, 0.03% molybdenum, 1.2% vanadium and 0.4% copper – and 30 other elements.

As rolled steel is a high-value alloyed segment that is produced at several sites in the Nordics, there should be a higher focus on developing more circular business models. Rolled steel from appliances and from the dismantling of cars could be separately processed and returned in closed circles to the rolling mills for direct reuse with a strict alloy framework.

If a closed-loop value chain is possible to develop, ownership of the metals will be less important. Ownership can then be transferred to hedge funds or raw material funds. These business models are known as precious metals and catalyst materials, where the industry stakeholders provide processing and logistical services but avoid having huge capital bound as material working capital.

169. Personal information from CEO of leading Nordic WEEE processing plant.

170. Daehn et al. Finding the Most Efficient Way to Remove Residual Copper from Steel Scrap. Metallurgical and Materials Transactions. 2019.

171. Paz et al. Recovery of Materials from Refrigerator: A Study Focused on Product Distribution, Recyclability and LCA Evaluation. Sustainability. 2024.

There are several smaller and specialised steelworks in the Nordic countries that can form part of such a value chain.

IRENA, the global RE association, has developed its own circular steel strategy, but is concerned by the problems of scrap impurities; "Recycling could be limited not just by the availability of scrap in quantitative terms but also by its quality. Contaminants such as copper and tin in steel scrap render scrap less usable for certain applications. These impurities come from the alloying elements from previous use cases or arise due to improper scrap management practices."^[172]

Potential for recycling of critical raw materials

Improved closing of the steel alloy value chain with increased sorting and avoidance of dilution loss will avoid the need for a very large input of CRMs in the range of tens of thousands of tons.

Existing steel infrastructure and existing products will largely be unaltered and perhaps become more resilient towards global competition.

Recycling plants will change, and new business structures will need to be developed to avoid contamination of the resources.

More efficient resource utilisation of CRMs results in less loss and, hence, less use of new CRMs and higher quality of recycled steel.

Barriers

Closing the value chain for certain steel alloys is impossible without changing parts of the recycling industry. Some of the existing industrial participants will mobilise resistance to change.

While technologically mature markets such as refrigerators/freezers and ventilation tubes etc., could quite easily develop rather closed structures, many of the other steel components are difficult to mobilize secure volumes at consistent composition.

Contaminant removal in the scrap sorting industry is focused on density and not elemental composition today. Improved technology for XRF or other sorting technologies is needed.

Possible means of actions/instruments

Governmental lease schemes whereby a state-financed body buys and stores certain specified CRMs or alloys and sells/leases this to industry stakeholders with limitations on where to sell and requirements on recycling. Variants of this have been used for several CRMs by the USA and Japan to secure their industry access and availability to material.

Governmental financing structures with soft loans for new business models where a group of industries develop a closed loop of materials can be an important way to move this development forward. European alloy standards for specific niches of production, like standards for mobile chargers, can also be an important instrument for this development.

Socio-economic impact

Increased sorting of alloys will also increase the predictability of offtake for the scrap processors and supply for the steel plants. However, this increased predictability will, on the other hand, reduce the possibility of making short-term arbitrary gains in markets that, from time to time, have very fluctuating prices and supply/demand shortfalls in overseas markets.

172. IRENA. Towards a Circular Steel Industry. 2023.

Increased alloy sorting will reduce the loss of critical and costly alloying elements into segments with no use – and even could be detrimental.

Increased sorting costs and changes to the scrap processing industry can be significant.

Description and Prerequisites

A successful implementation of this measure may benefit from the effects of the following other measures:

[4.2.1 R&D program for the development of better sorting technology](#)

[4.2.3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding](#)

[4.2.4 Disassembly of EEE components in discarded vehicles before shredding](#)

[4.2.5 Organized emptying and dismantling of hand-held fire extinguishers](#)

[4.3.6 Develop business models that enable the restart of closed CRM-recycling facilities](#)

Other variants of the measure

Specific segments of steel, such as the mentioned refrigerators, could be regulated only to allow one or a limited number of alloys so that closed circles can be established directly.

Large steel users, such as manufacturers of buses, personal vehicles, and appliances, may sell their items with an included deposit for takeback/return so that the manufacturer can establish their own circular value chain.

4.3.3 Develop business models that allow the establishment of networks of Nordic secondary aluminium works specialising in the recycling of specific alloy grades

Aluminium is a fantastic metal with versatile applications that can be modified in many ways by adding alloying elements. Indeed, there is almost no use of unalloyed aluminium – all end uses have alloy components added.

As the recipes for end uses are so different, recycling is challenging, and the quality of the output will suffer under current conditions. Separating specific aluminium alloys is only to a limited degree possible today. This may result in a need to add primary metal and primary alloying elements for dilution of contaminants. This will quite often result in a loss of valuable CRM-alloying elements, increasing CRM-consumption beyond what would otherwise be necessary. This situation leads to downcycling, where a steady stream of high-value aluminium alloys ends up as lower-quality casting alloys, where the tolerance for variations is much higher.

Included in recycling is the direct recycling of sorted alloys into primary production. Indeed, when primary aluminium enters alloying furnaces in the primary foundries, it is, too. If properly sorted scrap is supplied directly to the alloying furnace, it will both facilitate high-level recycling, it will save electricity, and it will speed up the time spent in the alloying at the foundry.

Recycling aluminium with specific alloy recipes in specialised facilities will result in higher resource utilisation of CRM-alloy components such as magnesium, beryllium and scandium.

The solution to this issue and the path to a more circular value chain goes through both increased sorting and a network of specialised alloy recycling plants. A secondary value chain for aluminium that recycles specific alloys will require more detailed sorting of scrap aluminium and recycling plants that specialise in recycling specific alloys. Although such a value chain will provide much more resource-efficient aluminium recycling, current market conditions make the profitability of such endeavours questionable. Business models should, therefore, be sought to allow for such operations, and a support scheme that makes these models economically sustainable should be established.

There are several smaller and specialised secondary aluminium plants in the Nordic countries that can form part of such a value chain. As most of the alloying elements are supplied from outside of Nordic (and mostly from outside of Europe), there is actually the possibility of developing new, small, specialised alloy production and recycling plants, preferably as organic growth within the existing industry structure. There were more of these small, specialised plants 20 years ago; dropping alloy prices below prices of primary aluminium resulted in the closure of many of the European and Nordic plants and the transfer of this niche competence to primarily Asian countries. With the establishment of CRMA and CBAM, this industry can be reestablished.

As the margins between mixed scrap and pure alloy scrap are significant, most players try to their best ability to have consistent and clean fractions. The industry has also made a solid effort to establish standardisation schemes.^[173] As for the sorting, companies such as Tomra,^[174] Steinert,^[175] Scanmetal^[176] and several others are making reasonable efforts to improve efficiencies.

Potential for recycling of critical raw materials

More efficient resource utilisation of CRMs and higher quality of recycled aluminium.

The aluminium industry in the Nordic countries represents about 3 million tonnes, of which 1 million is recycled. With approximately 1% of the recycled aluminium representing CRMs other than aluminium, the volume in circulation is in the region of 10,000 tonnes per year. Some of this comes to good use already by an acceptable level of recycling, while some come to partial use as downcycled material. Much of the CRM-content, however, is lost as the recycling mixes unfavourable alloys. Hence, the additional recycling potential represents thousands of tons of CRM.

Barriers

The most significant barrier seems to be the industrial policies and market position of competing economies outside of Europe that operate under protection regimes, which far outweighs similar support for the European Aluminium industry. Indeed, if any industry is prepared for efforts towards increased alloy circularity, the Nordic countries need to be prepared to support and protect such industry if these efforts are to succeed.

The need for mature technology for cold sorting of post-consumer scrap is the second important barrier. Statistics on aluminium recycling include process scrap recycled internally in factories or between alloy suppliers and customers of material that has never been used. Hence, almost all recycling of post-consumer aluminium alloy today includes either dilution or downcycling.

Most post-consumer aluminium scrap contains non-alloy contaminations, such as coatings, lacquers, screws, filings and dirt that will need to be either washed or burned off or metallurgically controlled in the furnaces.

173. <https://aluminium-guide.com/aluminium-scrap-standardisation/>

174. <https://www.tomra.com/en/waste-metal-recycling/products/machines/autosort-pulse>

175. <https://steinertglobal.com/applications/metal-recycling/aluminium-recycling/>

176. <https://scanmetals.com/>

Possible means of actions/instruments

High-end alloy recycling plants need some level of preferential treatment and protection to cover increased sorting and processing costs.

Subsidised financing of advanced equipment against an obligation of not exporting sorted, high-end alloys out of Europe should be considered. Only accept export of casting alloys.

New technology for fast and precise sorting of different alloys needs to be developed, which will probably require funding.

Socio-economic impact

Increased sorting and specialised alloy recycling will create a larger value per tonne of material and, henceforth, increase industry competitiveness. More importantly, access to specialised alloys will be increased for Nordic and European companies, decreasing dependencies on imports.

A rough and conservative estimation of an added value of DKK 1 per kg of sorted alloy and a recycling volume in the Nordic of 1 million tonnes equals increased GDP of the Nordic of DKK 1 billion together with increased recovery of respective CRMs together with a reduced negative environmental footprint.

Description and Prerequisites

A successful implementation of this measure may benefit from the effects of the following other measures:

[4.2.1 R&D program for the development of better sorting technology](#)

[4.2.3 More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding](#)

[4.2.4 Disassembly of EEE components in discarded vehicles before shredding](#)

[4.2.5 Organized emptying and dismantling of hand-held fire extinguishers](#)

[4.3.6 Develop business models that enable the restart of closed CRM-recycling facilities](#)

Other variants of the measure

Specific programs could be targeted towards small niches of aluminium components containing scandium and other elements of importance.

4.3.4 Establishment of a Nordic recycling plant for gallium from industrial wastes from zinc and aluminium

Establishing a Nordic plant for the recovery of gallium should be considered. The industry structure of the Nordics contains several large sources of gallium, of which nothing is recovered or recycled at the moment. The most interesting is probably the enriched dust from producing primary aluminium that could yield significant amounts of secondary gallium.

The Nordic countries have large amounts of waste of this type and are experts in current recycling technologies. Suppose a gallium recycling plant based on waste from the aluminium industry is set up; it might be possible to consider other industrial waste as well and add a gallium-rich WEEE fraction on the supply side.

Potential for recycling of critical raw materials

Gallium is mainly associated with aluminium resources and is today mainly produced by SX technology from Bauxite Bayer Liquor in China. In the Bauxite-Alumina process, the contained gallium is split with almost similar amounts in the alumina and the red mud, and in the primary aluminium processing – gallium is often enriched approximately ten times in particular dust, leaving the process and possibly also in other waste fractions.

Gallium has several chemical similarities with aluminium and will, to some degree, end up as a primary metal and a contaminant. This is unwanted and has a negative effect on the quality of the aluminium. Indeed, if the levels become too high, it might have a deleterious effect on aluminium corrosion and strength. Minor modifications to primary aluminium smelting that might decrease the percentage of gallium lost in the aluminium and instead migrate to the dust fractions is a benefit both for aluminium quality and recyclability as well as a feedstock for European gallium supply.

Indeed, the European primary aluminium producers are today the largest untapped source of gallium, and it is possible that the gallium content in landfilled waste from these plants surpasses the annual needs in Europe. This indicates that there might only be technological and economic barriers for the Nordic countries to make Europe gallium self-supplied. Today, Europe is entirely dependent on China for gallium supply.

Concentrations of gallium in alumina feedstocks vary significantly between different bauxite feedstocks. While the largest European player, Norsk Hydro, has its primary feedstock from low-gallium bauxite excavated in the Para/Amazon regions of Brazil – several of the other Nordic primary producers have access to high-gallium feedstocks. This is the case for the plants owned by Alcoa (Norway, Iceland), Rusal (Sweden) and Century (Iceland).

Gallium is also found in relevant concentrations in some other fractions, such as jarosite sludge from zinc refining and certain mica byproducts. It is possible at a later stage to consider the preprocessing and recycling of some of these volumes as well.

Barriers

Regulation on export and subsidised production by non-European countries makes it difficult for European industry to compete. Gallium extraction from dust and slags from primary aluminium has been proven and patented in several different R&D projects, but it is not commercialised, so upscaling and industrialisation are needed.

Possible means of actions/instruments

A ban on landfilling gallium-containing wastes at par with feedstocks used in the primary production of gallium (150 ppm) should be considered for the Nordic Countries.

A Nordic extraction plant could be built with a similar mandate to Nordic primary smelters on delivering wastes with >100 ppm (for example) of gallium.

A plant built with dust from Nordic primary aluminium smelters as base feedstock will also be able to receive material from LED processing. Specific sorting of LED diodes and preprocessing of such would be necessary.

Based on the low volumes, complex chemistry and external market manipulation, the expectations are that an extraction plant would need 100% CAPEX support and probably governmental price guarantees in line with US regulations under Inflation Reduction Act.

Socio-economic impact

Primary aluminium is a huge industry in the Nordics, so every regulation that reduces contamination in the metal and develops a byproduct stream can make the plants more resilient. As all the primary plants are located in remote rural areas, long-term positive residency effects might be experienced in these regions.

The main socio-economic impact will be indirect from the geopolitical aspects. As gallium is needed for all modern lighting (LED) and e-mobility (NIB-tech) and important for telecommunication and defence, access to sufficient feedstock is essential for political independence and modern life as we know it.

The direct number of workplaces and reduced landfilling of waste is expected to be limited.

Description and Prerequisites

An economic support scheme for R&D efforts towards better CRM-recycling technologies could be important for the successful preparation of a Nordic gallium recycling plant. If built, landfilling gallium-rich waste should be banned. A Nordic gallium recycling plant will likely need CAPEX support and price guarantees to become economically sustainable.

Other variants of the measure

Substantial amounts of gallium from feedstock end up in the primary aluminium. Hence, secondary aluminium may be a relevant feedstock when processed/treated in secondary refineries. As gallium is also a minor niche alloying element in aluminium, some gallium might be added to secondary refineries, increasing the relevance of gallium extraction from the metal. While several technologies have been developed for extracting gallium from primary smelting dust,^{[177][178]} so far, no one has developed a way to remove gallium from aluminium metal. Removal of gallium from metallic aluminium is considered very difficult; hence, gallium contamination will remain.

Gallium is also found in jarosite sludge from zinc refining. Technology for the extraction of gallium is less developed from such wastes. Still, if it is developed, large volumes of jarosite will be available, and co-extraction of germanium and indium (and perhaps other CRMs) could be possible.

4.3.5 Development of recycling process for circuit boards and other EEE waste that recovers more CRMs

A staggering 70 different elements are found in PCBs. However, not everything is everywhere and with very different concentrations from piece to piece and even from millimetre to millimetre on each piece.

Tonnages are large and increasing, and the metal content is high, making PCB an especially important waste stream from which to get better CRM-extraction.

Recycling of WEEE and PCB today largely focuses on recycling gold and copper, while other CRMs typically end up in the slag from the operation. The development of processes that also recycle other CRMs will be able to increase the resource utilisation of these waste streams.

The Nordics is a leading region in recycling circuit boards and other WEEE, as well as in technical and chemical expertise in this area.

177. <https://patents.google.com/patent/US4639355A/en>

178. Wang et al. Gallium recovery from aluminium smelting slag via a novel combined process of bioleaching and chemical methods. Hydrometallurgy. 2018.

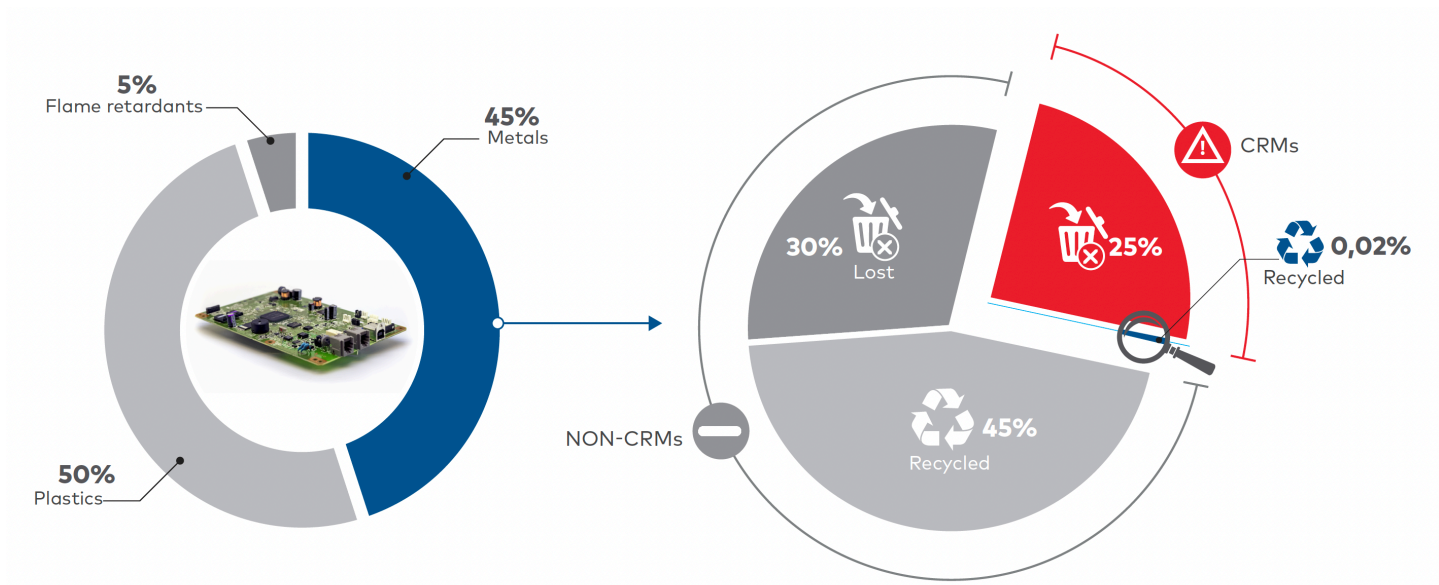


Figure 4.5 Printed Circuit Boards contain about 70 elements, but only about 20% of the content is recycled. Source: Bergfald Miljørådgivere.

Circuit boards are complex waste fractions with a high content of valuable materials. Gold is dominating the economic value and represents about half of the sales value of recovered metals from typical PCBs, while copper is the dominating material by weight.^[179] While copper is a CRM, gold is not, which contributes to some distractions in the recycling as profit potential of gold recycling will always get priority over the security of the supply of CRMs unless there is a mandate that correct for this.

The current recycling infrastructure has its industrial roots in the mining sector by refining copper concentrates and later extracting and refining associated metals such as gold, silver and PGMs.

While focus of the recycling operations operated by companies such as Boliden,^[180] Aurubis^[181] and Umicore^[182] is the gold and PGM content (combined about 0.05% of the weight) and, of course, copper with approximately 20%, while the content of non-recycled CRMs in the same feedstock is approximately 6.8%.^[183] Important CRMs that are found in PCBs and other WEEE and are not recycled include REEs,^[184] gallium^[185] and germanium.

It is assumed that new processing technologies will not negatively impact existing gold/copper industries. Indeed, the processing steps will either be added pre-processing or post-processing with little or no influence on the current process flow sheet. If there is any change, it might be an improvement, as removing the currently non-recycled CRMs might make gold/copper extraction easier.

179. Bergfald 2022. Mer Gjenvinning av Kritiske Råvarer. <https://renas.no/kritiske-ramaterialer/>
 180. <https://www.boliden.com/sustainability/case-studies/largest-electronic-material-recycler-in-the-world/>
 181. <https://www.aurubis.com/en/products/recycling/e-scrap-and-complex-raw-materials>
 182. <https://pmr.umicore.com/en/recyclables/e-scrap/>
 183. Bergfald 2024. <https://www.norden.org/en/publication/recycling-critical-raw-materials-nordics>
 184. Bergfald 2019. <https://www.bergfald.no/gjenvinning-av-sjeldne-jordarter/>
 185. Bergfald 2018. <https://renas.no/viktig-jakt-pa-sjeldne-metaller/>

New technologies for CRM-extraction from WEEE have been studied and tested in several development programs around Europe, including several involving Nordic industries and research organisations. These programs include hydrometallurgical, supercritical, biological and mechanical processing technologies. Many of these technologies are promising, they are maturing, and to some extent, it is possible to foresee a combination of technologies in operation. However, it is not yet possible nor wise to nominate a single technology path as a future dominant.

Potential for recycling of critical raw materials

About half of all PCBs that are placed on the market are delivered and sorted for recycling. Hence, the other half is either accumulated or lost. From the half that is delivered to recycling, only copper and PGM of the CRMs are recycled, which is less than 20% of the delivered content. The remaining 6,8% content of CRMs is not recycled. Even if the collection is not improved, the potential ranges in thousands of tons of CRM.

Barriers

The most important barrier against improved CRM-recycling of PCBs is the lack of mature recycling technologies. The current gold/PGM-focused recycling technology leaves REE and other CRMs classified in a slag. Totally new technology will need to be developed. If the technology for increased CRM-recycling is developed, it must be adapted by the current value chain, as the mentioned gold/PGM-stakeholders control the materials. The heterogeneous content of CRMs in EE-products makes both technological development and industrial investments highly risky.

PCBs are rich but small, so to industrialise, it will be helpful to pool resources and gather sufficient and foreseeable volumes. Increasingly, many of the PCBs are included in very small components that are difficult to locate and separate out for processing.

Significant volumes of PCBs are lost by legal and illegal export out of Europe and are often landfilled in the importing countries without sorting.

Possible means of actions/instruments

A support scheme for researching improved recycling processes for PCBs and other WEEE that recovers more CRMs and piloting these technologies should be considered. Recycling processes that lose non-recycled CRMs into a classified slag should be banned when improved recycling technologies become available. Financial derisking should also be sought through soft loans or loan guarantees for companies establishing new recycling plants implementing state-of-the-art CRM-recycling and minimum price guarantees for the CRMs recycled.

Socio-economic impact

Recycling of PCBs is currently a profitable industry with sustainable operations. The largest single stakeholder in the Nordic is located in the north of Sweden, but several other sites are located with different activities, mainly in rural areas spread around the Nordic countries. It is expected that the development of increased CRM-recycling from PCB will provide more revenue to these industries, as well as more industrial jobs.

Description and Prerequisites

Developing industrial processes that will allow better CRM-recovery from PCBs could be encouraged through economic support schemes described under [section 4.3.1](#) of the R&D program for the development of new or more efficient recycling processes.

Other variants of the measure

The highest concentration and diversity of CRMs are found in PCBs on smartphones. A dedicated strategy and, eventually, a processing plant for mobile phones would be the cherry-pick of the WEEE sector as the waste stream is small in volume but has large CRM-recycling potential.

Focusing on one or a limited number of CRMs from this segment, perhaps based on analysing the elements where PCBs are the most available CRM-source.

4.3.6 Develop business models that enable the restart of closed CRM-recycling facilities

Protecting existing CRM-recycling capacities from undue closure and developing mechanisms to help closed recycling facilities restart will most often be easier and less costly than developing new operations from scratch.

Business models should be developed that enable the restart of Nordic CRM-recycling facilities that have been shut down as a result of market manipulation.

The following examples from Norway illustrate the options in existing infrastructure.

1. High manganese steel recycling closed. Stavanger Staal in Rogaland received used mantles from crushers all over Scandinavia, especially steel with 20–24% manganese. These were remelted, new Fe-Mn-alloy from Sauda and scrap iron were added, and new mantles were cast. Due to a drop in prices, production closed in January 2023. New mantles to the crushers of Boliden, LKAB, Keliber, Titania and other critical mines will, in the future, be supplied mainly from China.
2. Magnesium alloy recycling is closed. Norsk Hydro produced primary, recycled, and alloyed magnesium at the Telemark site. After several years of low prices, the primary production closed in the year 2000. The 30,000-tonne recycling plant was put in care and maintenance in 2005, and it still is. Both the recycling furnace and the alloy furnaces are intact. All supply of magnesium to Europe since 2005 has come from China, Russia and Israel. Substantial scrap magnesium is now sent from Europe to China for recycling.
3. Zinc & lead recycling closed. Nyrstar operated a large and advanced recycling plant in Vestland, recycling zinc and later lead from complex industrial wastes. While neither zinc nor lead is classified as critical by the EU, they are by many other nations. The plant in Vestland was put in care and maintenance in 2020, and the complex waste was exported out of Europe for landfilling instead. Both zinc and lead are produced in Europe, but to a large degree from imported concentrates.

While all examples are from Norway, similar cases can be found in other Nordic countries as well. It should be mentioned that as Europe and the Nordic countries build new niche recycling plants in the years to come, better protection and support are needed. Small plants and small companies have no chance to compete with industries operating outside of Europe unless matching support schemes are established.

Potential for recycling of critical raw materials

Hundreds of thousands of tons of CRM-recycling capacity are idled in the Nordics and can be restarted within months with new ownership, proper financing and some minor maintenance investments.

Barriers

The barriers are financial, as it is more cost-efficient to export CRM-scrap/waste and import refined products.

Access to equity and financing in the private sector for recycling plants is hard to mobilise. If the private sector is expected to re-enter these segments, some level of investment guarantees should be considered.

CRM-recycling cannot be expected to be able to compete on an open market with non-European entities unless matching industry protection with tariffs is established.

Possible means of actions/instruments

Tariffs on import of CRMs from outside of Europe. Over time, USA has developed advanced systems from which Europe may learn.

CRMs should be included in a second CBAM tariff list. Many CRMs, for instance, metals such as magnesium, silicon and titanium, are associated with very high CO₂-emissions. As these metals are not included in the new EU Carbon Border Adjustment Mechanism, both primary and recycling plants in Europe face undue competition. This can be balanced out with a separate CRM-list added to the following EU CBAM list, using generic emission standards for these metals.

Export ban on CRM-containing waste/scrap from Europe.

Financing mechanisms, such as soft loans and a Nordic CRM-equity instrument. One model could be the Norwegian Nysnø private equity fund that currently invests in a minority position in new climate-relevant technology.

Socio-economic impact

Many of these idled plants are located in rural areas, so a restart that provides 20-100 industrial workplaces and local activity might have a stimulating effect on the local community.

Other variants of the measure

Export restrictions on certain CRM-wastes should be considered independently of the issue of the restart of idled recycling plants.

Soft financing may be paired with hard consequences. Private equity participants in recycling receiving soft financing may be asked to provide additional guarantees in case of closure of plants – increasing the cost and threshold for closure.

High-value materials, such as precious metals, are often rented or leased by industrial users rather than purchased. Similar models have been tested for some of the CRMs in the US and Japan, where the government purchases, stores, and manages these materials. Under this model, industries pay a fee and are obligated to recycle or return the materials. The risk of fluctuating prices of the materials is then transferred from the users and recycling plants to the government entity. Consequently, users are only exposed to the user fee and the recyclers are limited to a refining fee.

4.3.7 Development of technology for the extraction of CRMs from ash

Whenever residual waste or biomass is burned, the small content of inorganic components will generate an ash fraction. As the Nordic population generates about 500 kg of residual waste per year per capita – the amount of residual ash is large, with approximately 2.5 million tonnes of bottom ash and 0.5 million tonnes of fly ash. In addition, there are hundreds of biomass boilers in the Nordics, producing heat, power and steam – generating an additional 3 million tonnes of ash.

Perhaps surprisingly, the content of different elements in these three distinct different ash categories is not that dissimilar. However, some differences are obvious. Ash from Municipal Solid Waste Incineration (MSWI) have significantly higher concentrations of technological elements such as copper and gold (which indicates large volumes of WEEE enter waste incineration), while ash from biomass plants (BCHP) have significantly higher content of potassium, phosphorous and magnesium.

Ash contains all CRMs, albeit often in low concentrations. As ash from waste incineration constitute very large volumes, a recycling solution may be able to extract significant quantities of CRMs such as for example antimony, although the CRM-concentrations in ash are relatively low.

Nordic countries have good expertise in the chemical treatment of ash residues. Fly ash from MSWI has been treated and stabilised for many decades, in contrast to most other European countries. Substantial work has, over time, been put into the characterisation of the ashes, as well as looking for different treatment and utilisation methods. The focus has been on the avoidance of environmental harm (such as stabilising methods to avoid leakage of heavy metals) but also on technology for use as concrete and aggregate applications.

While projects have looked at extracting salts, zinc and silver from MSWI and bio ashes, there has not really been any dedicated effort to extract a broader group of CRM-elements.

The inflow of small WEEE into MSWI, as well as minor volumes of specialised medical equipment,^[186] results amongst others in many precious metals, with 1 tonne each of gold and PGM and 35 tonnes of silver ending up in ash from incineration annually.

In both the US^[187] and China,^[188] as well as several other countries,^[189] there has been extensive work on extracting CRMs from coal fly ash over the last decade.^[190] This research is now gradually having an influence on MSWI, with a focus on niche categories such as REE.^[191] This work could also mature into bio ash, as the volume of that segment is like that of MSWI ash – while the content of REEs is higher. The many pilot plants for hydrometallurgical coal ash extraction may be cause for optimism regarding this opportunity and should be explored also for waste incineration.

While the total tonnage of CRMs in ashes is high – the concentration is low, and the technological challenges are substantial. It is worthwhile trying to sort out CRM-rich components such as WEEE before being incinerated instead of trying to extract them from a diluted material.

186. Kokkinos et al. Recovery of Noble Metals (Au, Pt, Ir, and Ta) from Spent Single-Use Medical–Technological Products. *Minerals*. 2024.

187. DoE. Report to Congress. Recovery of Rare Earth Elements and Critical Materials from Coal and Coal Byproducts. 2022.

188. Zhou et al. Distribution and preconcentration of critical elements from coal fly ash by integrated physical separations. *International Journal of Coal Geology*. 2022.

189. Karan et al. Separation of coal combustion residue for critical element extraction and other bulk uses. *Env. Sci Adv.* 2024.

190. Dodbiba et al. Trends in Extraction of Rare Earth Elements from Coal Ashes: A Review. *Recycling*. 2023.

191. Zhang et al. Toward zero-waste resource recovery from municipal solid waste incineration ash by electrochemical and chemical mining. *Cell Reports Sustainability*. 2024.

Even if the volume of REEs in ashes amounts to 1,000 tonnes, it might be even more important to mobilise nutrients such as phosphorous and potassium, with their content of 60,000 tonnes and 220,000 tonnes, respectively.^[192] The main supply of phosphate to the Nordic countries, at the moment, is South Africa, while the main source of potassium is Belarus.

Potential for recycling of critical raw materials

The fact that large parts of incineration ash are already collected and processed has lowered the threshold for developing extraction possibilities.

Of the 1,000 tons of REEs in Nordic incineration ashes, 275 tonnes are magnet metals. As a perspective, if these REEs could be extracted with 100% efficiency, these metals cover the REE-needs necessary for making all cars sold in Sweden fully electric. Although the actual recovery efficiency will always be significantly lower than 100% the real amount of recoverable REE from ash will still be substantial

Barriers

The most important barrier is the lack of available recycling technology. However, as large projects now are working on coal fly ash, new technologies that could be adapted might mature.

Bio ash is generally not collected today but instead disposed of locally. Some volumes are returned to nature as fertiliser, but most are not. The current practice of forestry in the Nordic is draining nutrients, and recovery of these nutrients should be considered.

Possible means of actions/instruments

Improper or insufficient treatment of both bottom and fly ash can create significant issues for water courses, so the disposal is already regulated. Establishing a few central locations for the processing of ashes should be considered.

The introduction of an incineration fee of, for instance, DKK 20 per MWh of heat/power for both MSWI and biomass plants could be paid into a fund, from which companies that build CRM (and nutrient, salt, etc.) extraction plants can apply for funding. Increased grants for research and development into technologies for ash processing should also be considered. If the technology for efficiently recovering CRMs from ashes becomes available, using ash with high CRM and/or nutrient content in diluting applications such as concrete should be banned.

Socio-economic impact

A levy or fee on incineration to finance ash processing and CRM-extraction will make waste treatment costlier (i.e. increase taxation). It will reduce the competitiveness of biomass heat towards other energy sources. Such consequences must be evaluated before implemented.

If successful collection and processing value chains are established, thousands of tonnes of CRMs could be available, with very foreseeable feedstock supplies. These processing plants will generate income and jobs.

Water recipients that receive run off water from ash landfills are negatively influenced, but these costs are not calculated or estimated. By processing the ash, these natural costs will be reduced or avoided altogether.

192. <https://www.norden.org/en/publication/recycling-critical-raw-materials-nordics>

Other variants of the measure

Pre-sorting of bottom ashes where particles larger than, for example, 2 mm are used as an aggregate substitute, while smaller particles are chemically processed.

4.3.8 Rationalise the use of metal alloys that facilitate CRM-recycling

A large number of unique metal alloys are used for various products and materials. New alloys and applications for advanced alloys are developed rapidly, which often leads to improved product performance and versatility. However, with very few exceptions, the development of alloys does not have recyclability or the possibility of using recycled material as a priority or prerequisite. New alloys therefore often complicate later recycling and the future circular economy potential. Even if many products benefit from a more optimal alloy – the overall loss of material and energy during recycling represents a significant loss of resources and monetary value.

One way to improve this is by rationalising the use of alloys. This can be used by developing new alloys focused on using scrap-only.^[193] It can also be helped by increased standardisation of a smaller number of alloys for larger purposes of use, which will simplify the sorting of the alloys and enable more resource-efficient recycling of, amongst other things, CRMs. Restrictions on alloy compositions that make recycling difficult will be significant.

While metals like copper and alloys, such as bronze, have been available to humanity for millennia, most metals and alloys we use today have entered into human consumption relatively recently. The second biggest metal after iron is aluminium. Aluminium has only had relevant production for a little over 100 years. During that time, aluminium alloys developed. Indeed, even if the annual market for aluminium is approximately 100 million tonnes per year, almost all end up in different alloys.

These alloys give fantastic possibilities for tailoring the material performance to the end-use application and providing fast and exciting development of different products. However, the same diversity and flexibility in modifying performance in the first use of a product creates at least similar levels of complexity and challenges in recycling. When almost no similar types of products are made with the same alloy, recycling becomes difficult, and both recovery efficiency and quality of recycled materials will suffer.

Whether considering window frames, automotive chassis or computer housing, almost all OEMs have their dedicated alloy to stand out from the crowd.

193. Gaustad et al. Design for Recycling – Evaluation and Efficient Alloy Modification. Journal of industrial Ecology. 2010.

First flight	Aircraft	Alloy and Temper
1903	Wright Brothers	Al-Cu casting
1919	Junkers F13	2017-T4
1935	DC-3	2024-T3
1939	Zero Fighter	ESD-T6
1945	B-29D (B-50)	7075-T651
1957	Boeing 707	7178-T651
1970	DC-10	7075-T7351
1970	L-1011	7075-T7351
1981	Boeing 757, 767	2324-T39, 7150-T651
1994	Boeing 777	7055-T7751, 2524-T3
2003	Boeing 777-300ER	2324-T39 Type II (2624-T39)

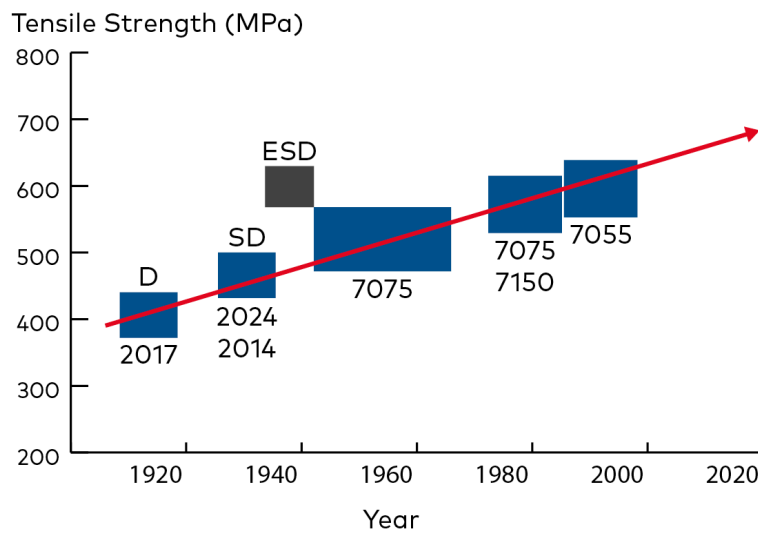


Figure 4.6 Example of improved strength-to-weight ratio in aircraft alloys over 100 years. Data source: Yoshida, H.^[194]

194. Yoshida, H. History of the Development of Extra Super Duralumin and Future Research Issues of AlZnMg Alloys. Materials Transactions. 2023.

It should be expected that the most important improvements have already been made in the first 100 years of development for a metal such as aluminium and that further improvements will mainly be incremental. If this is an acceptable assumption, the benefits of standardisation of alloys for major consumption niches would outweigh the possible incremental improvements.

While industry associations and standardisation organisations have done remarkable work in establishing standard definitions of alloys, there are almost no restrictions or guidelines on where alloys should be used.

Keeping with the example of aluminium, it should be considered if aluminium window frames, automotive chassis, and computer housings are only made from certain specific and defined alloys. This has, as a matter of fact, been proposed many times by different industries and scientists over the last decades – but with little acclamation so far.

Actual alloy restrictions will provide a double benefit to the CRM-recycling:

- Recovered fractions can be used directly without blending and topping up with new CRMs (such as copper, magnesium etc.)
- As pure fractions are separated, CRMs in use will not be lost into inferior alloys.

Minor CRM elements used as alloying elements in major metals such as copper, steel or aluminium will be lost forever if it is not separated back into the same alloys or somehow extracted in a recycling process.

Larger components, such as long HV cables, whole auto chassis and facade plates, can easily be exempt from any regulations, as it is easy to establish closed or semi-closed value chains from large components. The alloy recycling difficulty is mainly concerning the myriads of small components with slightly different alloys.

In the aluminium market, alloys are developed for different uses and processing technologies, such as rolled, pressed, wrought and cast alloys. In general, casting alloys are the most forgiving regarding contaminants, so general and non-specific aluminium scraps end up as casting alloys.

It can be mentioned that one interesting benefit of the technology disruptions initiated by the US company Tesla is the aluminium giga presses. While traditional construction of auto chassis used different smaller components in different materials and alloys that were welded, screwed or glued together, the Tesla Giga press makes the whole chassis in one piece – and then also in one alloy.

Potential for recycling of critical raw materials

- More resource-efficient recycling of alloys
- Reduced use of many CRMs
- Increased value of recycled metal fractions

Barriers

The recycling industry is developing quickly, and many impressive results have already been observed. However, a large part of the industry is still more occupied with handling waste than providing feedstocks. The biggest challenge would be to mature the recycling industry from waste disposal to high-tech circularity.

Establishing standardised alloys for segments such as computer casings, phone casings, automotive chassis, window frames, windmill towers will limit the possibility of technical and material improvements and could also limit the competition to some degree.

If no standardization takes place, efficient aluminium recycling will most likely require the establishment of hundreds of different alloy collection and recovery material streams. This will both be more costly and require more manual labour and transport.

Possible means of actions/instruments

One possible instrument will be to mandate environmental product certification schemes covering metals to only accept standardised alloys.

All users of alloys containing a minimum amount (0.1%) of a listed CRM should be required to consider whether the benefit of using those alloys is justified compared to the implied supply risk. In other words, consider whether using alloys without CRM-content would be sufficient.

All components weighing more than 100 grams should be marked/stamped with a specific alloy number.

All components weighing more than 100 grams should be banned from using non-standard alloys.

Automatic XRF sorting systems need to be improved and possibly subsidised.

Socio-economic impact

The cost of recycling will increase, possibly more than the added value of pure alloys.

At present, advanced wrought and pressed aluminium alloys tend to end up as casting alloys when recycled. Prices of casting alloys typically range 10–30% below prices of wrought and pressed alloys, representing a significant value loss.

While the Nordics are a large producer of primary aluminium, the region also represents at least 1.7 million tonnes of production. With typical alloy prices in the range of USD 3 per kg, this means that if current recycling technologies result in a 10% lower value of 500,000 tonnes of aluminium scrap, society is losing 150 million Euro in value every year. Significant parts of this value loss can be avoided with dedicated scrap-based alloys, standardised alloys, marking and improved recycling technologies.

Description and Prerequisites

- Mandated standards for the use of only specific alloys for certain applications.
- New alloys are developed based on available mixed scrap in the years ahead.
- Improved labelling of components.
- Ban on welding and glueing of different alloys together—only mechanical joining.
- Development of separate recycling paths for larger components and known materials.

Other variants of the measure

Some variants of these measures are already in place (Danish reference on aluminium alloy or sorting).

5. Discussion and conclusion

Critical raw materials are necessary for the development of a modern society, sustainable technologies and the defence of our democracy. Much of the needed critical raw material can be found in specific waste fractions from some Nordic industries and some used items and products. In the first report of this series, it was shown that almost one million tonnes of CRMs are lost in different Nordic waste streams every year.^[195]

Recycling operations and a circular economy can only be sustained over time by being part of an intact value chain that includes collection, sorting and pre-treatment of waste used as feedstock for the recycling operation. Therefore, a national strategy for increased and improved CRM-recycling should consist of steps to ensure healthy and well-functioning operations at all central steps in this value chain.

The same recycling operation also depends on market demands for the secondary CRMs that are being recovered at prices that make the recycling operation profitable. If such a market doesn't already exist a CRM-recycling strategy should also include steps to develop such market conditions.

Figure 5.1 presents an overview showing which part of the value chain the sixteen measures discussed in [Chapter 4](#) of this report address. Although not shown in the illustration, these measures also impact at least one of the five milestones presented in the first report of this report series.

195. <https://www.norden.org/en/publication/recycling-critical-raw-materials-nordics>

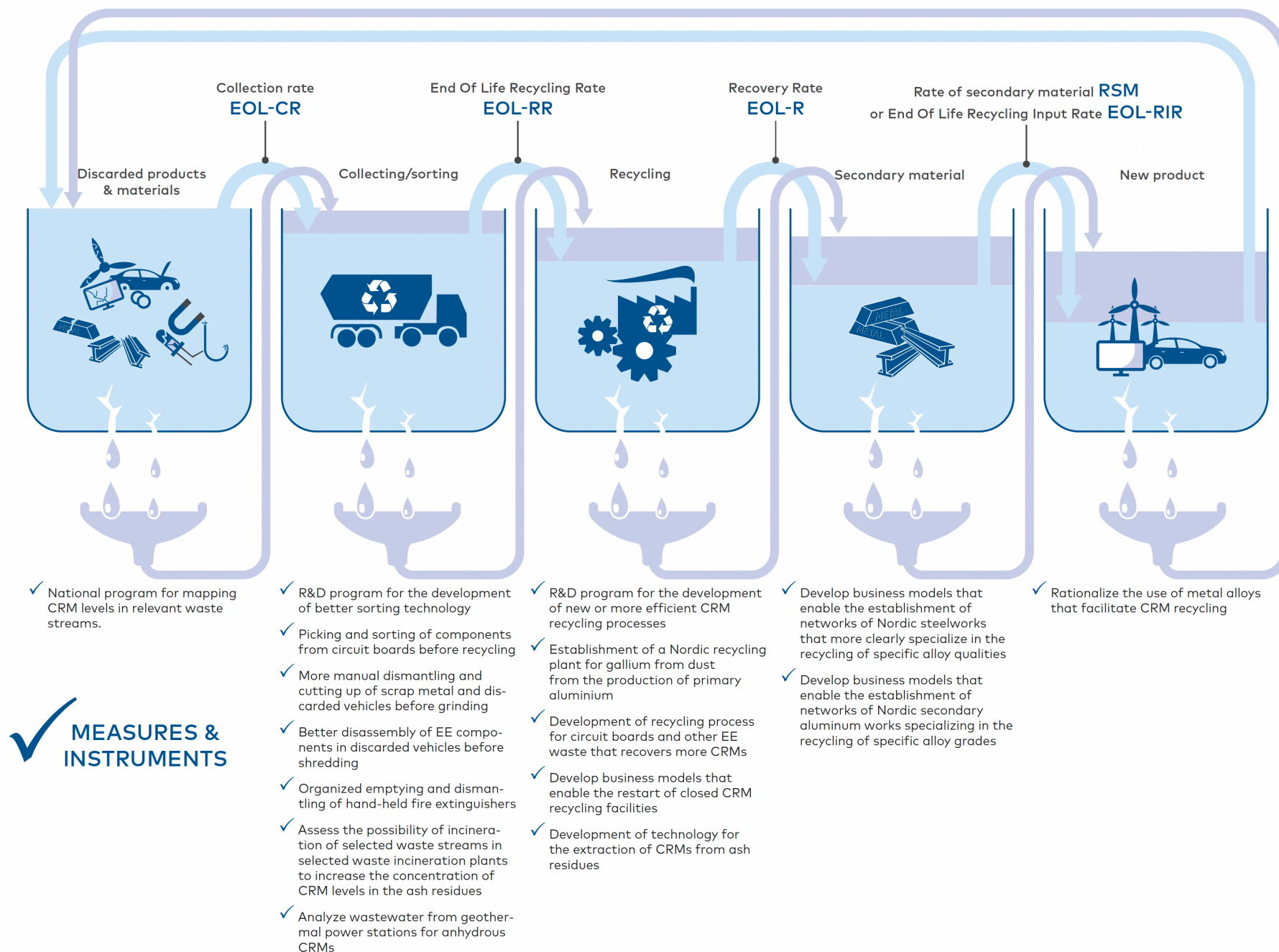


Figure 5.1 Possible measures and instruments for increased Nordic CRM-recycling. Illustration: Bergfald Miljørådgivere.

The measures include activities that collect necessary data, such as information about waste streams that may serve as new feedstock for CRM-recycling. It discusses establishing a national program for mapping CRM-levels in relevant waste streams or wastewater or assesses the CRM-recycling potential of different ash types from incineration processes. It contains measures for better sorting and pretreatment of waste before CRM-recycling like stripping waste electronics of components that should be recycled in separate recycling processes, better disassembly of EEE-components from scrapped cars before shredding and more thorough separation of specific alloys when collecting metal scrap that will ensure higher quality secondary CRM-materials. It also describes measures for updating existing business models for the aluminium and steel sector that will allow better recycling of CRM-components in alloys. There are also measures for establishing new CRM-recycling operations, such as building new plants or restarting Nordic CRM-recycling plants currently closed.

While the Nordic countries prefer that private companies operate industries, it is also important to acknowledge that such industries need proper operating conditions and protection against undue competition from countries with authoritarian agendas.

Finally, there are measures for accelerating the development of better technological solutions for tasks and processes that today represent technical barriers against more efficient CRM-recycling, including economic support schemes that are considered crucial for Nordic success in this area.

Not all measures described will be relevant for all Nordic countries, but all Nordic countries will eventually need access to all the CRMs coming from future recycling operations. Upgrading business models for the aluminium and steel industry will obviously only apply to countries with such industries. The steel industry in Sweden and Finland and the aluminium industry in Norway and Iceland are considered the most significant. Examining the CRM-recovery potential of wastewater from geothermal power stations is probably only relevant for Iceland. Coordination of efforts between the Nordic countries may also be beneficial as this will allow for common resources to be pooled when setting up support schemes and can help avoid unnecessary overlapping tasks.

All measures described in this report should be considered when setting up a national program for increased and better CRM-recycling. In addition to the 16 measures evaluated in Chapter 4, 69 additional measures are summarised in [Appendix Table 2](#).

All national programs should include measures for mapping waste streams with CRM-recovery potential, as this is also a requirement of CRMA. All programs should include systems for cost-effective collection of waste streams that can be CRM-recycled, as well as improved recycling processes. However, the design of these measures may vary due to different national conditions.

Each country can only establish specific recycling operations for some CRMs. All Nordic countries should, however, seek to have a coordinated role in building a regional network of recycling operations that expands and supplements existing European secondary CRM-production. This should be done by focusing on specific CRM-recycling where national competitive advantages can be identified.

Technical barriers limit the potential for reducing the CRM-material loss throughout the value chain at several stages. Today's sorting and pretreatment of many waste streams that contain recoverable CRMs are a particular concern as large amounts of CRMs are lost due to imperfect sorting and separation of material fractions that need to be recycled separately for optimal CRM-recovery to take place. There is an urgent need for massive R&D efforts towards more intelligent and robust automated sorting solutions that allow for resource- and cost-efficient separation of individual alloys and component stripping of WEEE. Another crucial R&D area that

needs increased public support is for improving available recycling processes. Many of today's dominating recycling processes recover only a few, if any, of the CRMs found in the waste used as feedstock. There are also many CRMs for which recycling processes for post-consumer waste have yet to be developed. This means that until such technology is made available, no CRM-recycling from these waste streams can take place, even if there is an economic incentive to do so. It seems unlikely that the necessary improvements needed for these technologies will occur in the near future unless significant public R&D funding is made available for this purpose. The Nordic countries already possess a leading role in automated waste treatment and CRM-recycling. Through coordinated efforts, this position can be strengthened further by making improved CRM recycling technologies available that can increase CRM-recovery not only in the Nordic countries but also in other countries that want to purchase the same technology.

One example of a strategic instrument that may play a role in strengthening R&D efforts towards these goals is the *Partnership on Raw Materials for Green and Digital Transitions* which is a new European co-funded funding scheme that aims at supporting lower to medium Technology Readiness Levels.^[196] Other relevant European funding instruments that could be considered include Horizon Europe and EIT Raw Materials Calls.

This report aims to be used as a toolbox of possible measures that can be applied to improve CRM recycling. As such, it represents an early attempt at presenting an overview of potential initiatives. The 85 measures listed in this report should not be considered as a final list as future examinations may lead to the formulation of additional concepts and improved understanding.

196. https://www.era-min.eu/sites/default/files/publications/eramin_sria_final_final.pdf

Appendixes

Appendix 1 Table: Companies and projects that may lead or take part in new or better CRM-recycling operations

Potential CRM	Company/Project	Process	Possible role	Country
Al	Rio Tinto Iceland	Primary aluminium smelter	New Ga or Al recycling	Iceland
Al	Norðurál	Primary aluminium smelter	New Ga or Al recycling	Iceland
Al	Alcoa Fjarðarál	Primary aluminium smelter	New Ga or Al recycling	Iceland
Al	Rusal i Kubal	Primary aluminium smelter	New Ga or Al recycling	Sweden
Al, F, Ga	Hydro Aluminium, Høyanger	Primary smelter	New Ga or Al recycling	Norway
Al, F, Ga	Hydro Aluminium, Karmøy	Primary smelter	New Ga or Al recycling	Norway
Al, F, Ga	Hydro Aluminium, Sunndal	Primary smelter	New Ga or Al recycling	Norway
Al, F, Ga	Hydro Aluminium, Årdal Metallverk	Primary smelter	New Ga or Al recycling	Norway
Al, F, Ga	Sør-Norge Aluminium Kvinnherad	Primary smelter	New Ga or Al recycling	Norway
Al	Hydro Aluminium rolled products Holmestrand	Secondary smelter	New Ga or Al recycling	Norway
Al	Hydro Vigelands Brug AS Vennesla	Reffinery	Increased or more alloy specific Al recycling	Norway
Al, F, G	Alcoa Mosjøen	Primary smelter	New Ga or Al recycling	Norway

Al, F, G	Alcoa Lista	Primary smelter	New Ga or Al recycling	Norway
Al	Metallco aluminium AS, Vestre Toten	Foundry/recycling	Increased or more alloy specific Al recycling	Norway
Al	Benteler Aluminium Systems, Raufoss	Foundry	Increased or more alloy specific Al recycling	Norway
Al	Hydal Aluminium Profiler AS Raufoss	Extrusion	Increased or more alloy specific Al recycling	Norway
Al	Speira, Rød	Recycling aluminium from slag and dross	New Ga or Al recycling	Norway
Al	Speira, Rausand	Recycling aluminium from slag and dross	New Ga or Al recycling	Norway
Al	Kuusakoski Oy, Espoo	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Kuusakoski Oy, Heinola	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Pirsu Oy, Ikaalinen	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Nordic Aluminium Ltd, Kirkkonummi	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Kuusakoski Oyj, Myllyoja	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Purso Oy, Siuro	Secondary smelter	Increased or more alloy specific Al recycling	Finland
Al	Stena Gotthard, Kolding	Secondary smelter	Increased or more alloy specific Al recycling	Denmark

Al	Isal (Rio Tinto) Hardarfjörður	Secondary smelter	Increased or more alloy specific Al recycling	Iceland
Al	Aluvest SA, Eidsvaag	Secondary smelter	Increased or more alloy specific Al recycling	Norway
Al	Chassix Norway AS, Farsund	Secondary smelter	Increased or more alloy specific Al recycling	Norway
Al	Ranalum AS, Karlsund	Secondary smelter	Increased or more alloy specific Al recycling	Norway
Al	Mosjøen Metall AS, Mosjøen	Secondary smelter	Increased or more alloy specific Al recycling	Norway
Al	Stena Gotthard, Älmhult	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Profilgruppen AB, Aseda	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Nemak, Charlottenberg	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Gränges Aluminium, Finspång	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	International Aluminium Casting Sweden AB, Gothenburg	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Gränges Aluminium, Gränges	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	AB Elektrokoppar, Helsingborg	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Sapa (Hydro), Sjunnen	Secondary smelter	Increased or more alloy specific Al recycling	Sweden

Al	Volvo, Torslanda	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	AB Lundbergs Pressgjuteri, Vrigstad	Secondary smelter	Increased or more alloy specific Al recycling	Sweden
Al	Alcoa Fjarðal, Fjarðal	Primary smelter	Increased or more alloy specific Al recycling	Iceland
Al	Nordic Aluminum Co (Nordural), Grundartangi	Primary smelter	Increased or more alloy specific Al recycling	Iceland
Al	Rio Tinto Alcan Iceland Co Ltd. (Isal), Straumsvík	Primary smelter	Increased or more alloy specific Al recycling	Iceland
Mn	Eramet Porsgrunn Telemark Porsgrunn	Si-Mn smelter	Mn recycling	Norway
Mn	Eramet Norway AS, Sauda	Fe-Mn smelter	Mn recycling	Norway
Mn	Eramet Norway Kvinesdal	Si-Mn smelter	Mn recycling	Norway
Mn	Ferroglobe Mangan, Mo i Rana	Fe-Mn & Si-Mn smelter	Mn recycling	Norway
Si	Wacker Chemicals, Hemne	Smelter	Si recycling	Norway
Si	Elkem Bremanger	Si & Fe-Si smelter	Si recycling	Norway
Si	Elkem Thamshavn	Si & Fe-Si smelter	Si recycling	Norway
Si	Elkem Salten	Smelter	Si recycling	Norway
Si	Finnfjord, Lenvik	Smelter	Si recycling	Norway
Si	Elkem ASA Bjølvfossen	Fe-Si & Mg-Fe-Si-smelter	Si recycling	Norway
Si	Elkem Rana AS Rana	Fe-Si smelter	Si recycling	Norway
Si	Bakkisilicon	Si metal smelter	Si recycling	Iceland
P	Yara Herøya	Fertilizer plant	Off taker for recycled P	Norway
P	Yara Glomfjord	Fertilizer plant	Off taker for recycled P	Norway

P	Yara Suomi Oy, Uudenkaupungin tehtaast	Fertilizer plant	Off taker for recycled P	Finland
P	Yara Suomi Oy, Kokkolan Tehtaast	Fertilizer plant	Off taker for recycled P	Finland
P	Yara Suomi Oy, Särkikanta, Siilinjärvi?	Fertilizer plant	Off taker for recycled P	Finland
P	Yara Siilinjärvi (REE og PO4)	Recycling project?	Secondary P production	Finland
P	Siilinjärvi Yara	Mine	Source of recyclable CRM-waste streams	Finland
PO4	HIAS	P-recycling	Secondary P production	Norway
PO4	Ash2Phos, Ragnsells	P-recycling	Secondary P production	Sweden
Cu, Ni	Boliden Harjavalta	Smelter	Increased Cu and Ni recycling	Finland
Cu	Boliden Kokkola	Zinc Smelter	Increased Cu recycling	Finland
Cu	Boliden Odda	Zinc Smelter	CRM-recycling from jarosite sludge	Norway
Cu, PGM	Boliden Rönnskär	Primary and secondary smelter with hydrometallurgical steps	Increased CRM-recycling	Sweden
Cu	Boliden Atik	Mine	Source of recyclable CRM-waste streams	Sweden
Cu, (Au, Te)	Boliden Mines (Renström, Katrineberg & Kankberg)	Mine	Source of recyclable CRM-waste streams	Sweden
Cu	Boliden Garpenberg	Mine	Source of recyclable CRM-waste streams	Sweden
Cu, Ni, Co & PGM	Boliden Kevitsa	Mine	Source of recyclable CRM-waste streams	Finland
Ni, Co	Nornickel, Harjavalta	Hydrometallurgic plant	Increased Ni, Cu, Co recycling	Finland
Ni, Cu, Co & PGM	Nikkelverk, Kristiansand	Hydrometallurgic plant	Increased Ni, Cu, Co recycling	Norway

Cu, Ni	Terrafame	Mine and refinery	Source of recyclable CRM-waste streams	Finland
Ti	Kronos Titan	TiO2 refinery	Expertise in titanium raw materials	Norway
Ti	Tizir Titanium & Iron	Titanium recycling	Recycling of titanium raw materials	Norway
Ti, Ni Co & Cu	Titania	Ilmenite mine	Raw material supplier for titanium metal production	Norway
Ti	Nordic Mining	Rutile mine	Raw material supplier for titanium metal production	Norway
Co, Cu, PGM	Umicore Kokkola	Co recycling and refinery	Increased Corecycling	Finland
Cu	Pyhäsaari, First Quantum Minerals	Cu-Zn Mine	Source of recyclable CRM-waste streams	Finland
Ni	Mondo Minerals	Mine	Source of recyclable CRM-waste streams	Finland
Sb	Boliden Bergsöe	Secondary lead smelter	Increased Sb recycling	Sweden
Sb	Sala Bly	Secondary lead smelter	Increased Sb recycling	Sweden
Cu	Zincgruvan, Lundin Mining	Mine	Increased CRM-recycling	Sweden
Graphite	MRC Skaland Graphite, Senja	Graphite mine	Source of recyclable CRM-waste streams	Norway
Graphite	Vittangi, Talga Resources/Talga AB	Mine and refinery	Increased graphite recycling	Sweden
Graphite	Woxna graphite, Leading Edge Materials	Synthetic graphite production	Chemical graphite recycling	Sweden
Graphite	Bergen Carbon solutions	Synthetic graphite production	Chemical graphite recycling	Norway
Graphite	Vianode	Synthetic graphite production	Chemical graphite recycling	Norway

Graphite	Superior Graphite	Battery grade graphite production	Increased CRM-recycling	Sweden
Graphite	Akku Minerals	Graphite mining	Increased CRM-recycling	Finland
Ni, Mn, Co, Li, graphite	Hydrovolt	Li-ion battery recycling	Increased CRM-recycling	Norway
	NanoPow	Battery anode material production	Increased CRM-recycling	Norway
FMG	FMG	Battery materials (CAM and pCAM)	Increased CRM-recycling	Finland
	Stena Recycling	battery recycling	Increased CRM-recycling	Sweden
V, Ni	Häggån, Aura Energy, Vanadis Battery Metals	Mining project	Increased CRM-recycling	Sweden
Ni, Mn, Co, Li	Northvolt Skellefteå	Li ion battery recycling	Increased CRM-recycling	Sweden
Li	Kelliber	Litium mining and refining	Increased CRM-recycling	Finland
V, REE	Ormbäcken, Eurobattery Minerals,	Mine	Increased CRM-recycling	Sweden
Fe	Outokumpu, Tornio Works	Steel production	Increased CRM-recycling in alloys	Finland
Fe	Outokumpu, Nyby Operations	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Outokumpu Degerfors Operations	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Ovako Smedjebacken	Steel mill	Increased CRM-recycling in alloys	Sweden
Fe	Outokumpu Avesta	Steel mill	Increased CRM-recycling in alloys	Sweden
Fe	Outokumpu Avesta Operations	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Ovako Hofors	Steel mill	Increased CRM-recycling in alloys	Sweden

Fe	SSAB Oxelösund	Steel mill	Increased CRM-recycling in alloys	Sweden
Fe	SSAB Luleå	Steel mill	Increased CRM-recycling in alloys	Sweden
Fe	SSAB	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Celsa Armeringsstål, Mo i Rana	Secondary steel smelter and foundry	Increased CRM-recycling in alloys	Norway
Fe	HYBRIT	Steel mill	Increased CRM-recycling in alloys	Sweden
Fe	Höganäs	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Alleima	Steel production	Increased CRM-recycling in alloys	Sweden
Fe	Ovako	Steel production	Increased CRM-recycling in alloys	Sweden
V	Neometals	Recycling V from steel slag	Increased V recycling	Finland
V	Skåne Vanadium Project, Province Resources	Mine	Source of recyclable V-waste streams	Sweden
REE & P	Per Geijer, LKAB	Reprocessing of tailings	Increased CRM-recycling	Sweden
REE	Norra Kärr REE, Leading Edge Materials	Reprocessing of tailings	Increased REE and P recycling	Sweden
REE & P	Grangex	Reprocessing of tailings	Increased REE and P recycling	Sweden
REE, P & F	ReeMAP, LKAB	Reprocessing of tailings	Increased REE and P recycling	Sweden
LREE	REEtec	Refinery	Increased REE recycling	Norway

Appendix 2 Table: Extended list over possible measures and instruments

ID	Name of initiative	Explanation	Objective and intended effect/expected impact
Mapping CRM-waste streams			
A1	National program for mapping CRM-levels in relevant waste streams.	Identification of waste streams suitable for CRM recycling requires a minimum of information on the chemical composition of the waste. For many materials and waste streams, knowledge about the content of CRMs is very deficient. A national mapping program can ensure a systematic and sufficiently detailed description that allow waste streams that can serve as feedstock for new CRM recycling to be captured. Before mapping takes place, which waste streams are to be included in the mapping must be decided together with which parameters are to be monitored beyond CRM concentrations, as well as how sampling and data recording are to be carried out. Ownership of the data base and access rights should also be clarified. It should also be considered how the mapping program can be included as part of a more complete description of the CRM materials' life cycle movement through the technosphere. Collected data should be registered in a national database that has been set up in line with guidelines from CRMA.	Knowledge of CRM content and associated material properties is a prerequisite for identifying waste streams that may be relevant for CRM recycling, and an initial assessment of which recycling technologies that may be relevant for such recycling
A2	Establish a Swedish materials technology laboratory	Establish a Swedish materials technology laboratory corresponding to Metso/GTK in Finland and SINTEF/NTNU in Norway for more coordinated collection and description of the CRM potential in mineral residues.	More coordinated collection and description of the CRM potential in mineral residues.
A3	Develop standardized test methods for investigating the potential for CRM recovery from mineral residues	The mapping of CRM levels and other relevant properties of mineral wastes should be carried out using suitable and representative sampling methods and chemical and material engineering analysis methods. For wastes of special interest, it should be a goal that the investigation provides a three-dimensional description of variations in CRM levels and other properties throughout the masses. The test methods should also be based on a common standard that ensures comparable results between different waste streams and apply to tailings, waste rock and discarded ore..	Standardized and scientifically sound sampling techniques and analysis methods will ensure comparable, high-quality test results.

A4	Development of a common Nordic database for describing the CRM recycling potential of different waste streams	"Although describing the CRM recycling potential of different waste streams is a national responsibility, it would be an advantage if the database through which this mapping is done follows the same template in all Nordic countries. If the EU Commission does not develop a common template for this, it would be rational for the Nordic countries to cooperate on developing a common template for this, which would not only distribute the development costs among several parties, but also utilize expertise that is not necessarily equally available in all individual countries. A common database template would also simplify assessments across the Nordic borders.	A common Nordic database template for describing the CRM recycling potential of different waste streams will reduce development costs per country, provide better access to collective expertise and simplify assessments across Nordic borders.
A5	Mapping CRM content in historical landfills	The National Geological Survey is tasked with investigating the CRM content of historical tailings dumps. The mapping should build on studies already conducted.	Publicly available information that makes it possible to assess CRM resource potential in different tailings masses, as well as fulfill Article 27 of the CRMA.
A6	Mapping CRM content in active landfills	Mining companies are required to report CRM content in active tailings landfills	Publicly available information that makes it possible to assess CRM resource potential in different waste streams
A7	Mapping CRM content in active industrial landfills	Industrial companies are required to report CRM content in their waste landfills.	Publicly available information that makes it possible to assess CRM resource potential in different waste streams
A8	Mapping CRM content in historic industrial landfills	Relevant professional body is assigned to investigate CRM content in historical industrial landfills.	Publicly available information that makes it possible to assess CRM resource potential in different waste streams
A9	Mapping CRM content in active landfills	Landfill owners are required to report CRM content in their own landfills	Publicly available information that makes it possible to assess CRM resource potential in different waste streams
A10	Mapping CRM content in historical landfills	Relevant professional body is assigned to investigate CRM content in historical landfills.	Publicly available information that makes it possible to assess CRM resource potential in different waste streams

A11	Mapping of CRM content in slag, dust and sludge from the metal processing industry	Industrial companies are required to report CRM content in all relevant outgoing material streams. CRM content should be investigated every two years to capture changes in chemical composition over time. The survey should include, among others, EAF dust, jarosite sludge, SPL, dross, etc.	Publicly available information that makes it possible to assess CRM resource potential in different waste streams
A12	Mapping of CRM content in Nordic alum shale waste from ongoing projects	Projects that generate alum-shale-containing masses are required to report CRM content in these masses.	Alum shale is a problematic waste that requires special handling and the final treatment is associated with significant costs. However, alum shale also contains recoverable CRMs in some cases. CRM recovery could perhaps be built into the final treatment of alum slate without unacceptably high additional costs.
A13	Mapping of CRM content in historical alum shale landfills	Relevant professional body is commissioned to investigate CRM content in historical alum shale deposits	Alum shales in some cases contain recoverable CRMs.
A14	Establishment of a database for mineral residues from completed mineral projects	Article 27-4 of the CRMA requires all member states to establish a database containing relevant information on the CRM content of mineral tailings from completed mineral projects. The database shall include information on the location of the tailings, area use, quantities of mineral waste with associated CRM concentrations, and information on historical owners and operators. In cases where it can be documented that the tailings do not contain relevant CRM quantities, an exemption from this requirement may be granted.	Simplify access to information about mineral residues with CRM recovery potential and fulfill Article 27-4 of the CRMA.
A15	Accounting for CRM material flows in national statistical accounts	The national statistical authority ensures that statistics on products, materials and waste are compiled that enable the material flow of CRMs to be traced through the life cycle of significant products and materials in line with the guidelines in the CRMA including Article 26-7 on CRM-containing components in WEEE. The statistical basis must have a form and level of detail that enables the evaluation of progress in relation to recycling targets for individual CRMs, and must thus be more detailed than current waste statistics. The statistical basis should also have a form that enables the overall assessment of European target achievement ref Article 44 of the CRMA.	To understand the movements of CRM-enriched material flows through society, a statistical accounting of the total market consumption of CRM and corresponding waste flows is necessary. Nordic countries already keep national statistics on products placed on the market and various waste flows, but these statistics do not include CRM material flow movements..

Collection and pretreatment

B1	Design and construction of buildings and infrastructure that support easy identification and separation of CRM-rich materials during future remediation and demolition.	Buildings and infrastructure are currently constructed without consideration for the possibility of recycling the CRM content of the building materials. This means that materials are produced and installed in ways that often prevent rational sorting of CRM-enriched waste during subsequent demolition. In addition, information is rarely available that makes it possible to identify building materials with CRM recycling potential. By taking this perspective into account when producing building materials, designing architectural and construction plans, and carrying out construction work, future sorting and collection of construction and demolition waste with CRM recycling potential can be carried out more efficiently.	Better labeling and product design for construction products and materials will enable more efficient sorting of construction waste with CRM recycling potential. This in turn could reduce the total amount of construction waste sent to landfill and incineration.
B2	Separate collection and delivery of CRM-enriched waste to relevant recycling facilities	Joint collection of CRM-containing waste with other waste fractions will normally lead to mixing, which could make subsequent sorting and pre-treatment before recycling more difficult and expensive. For this reason, separate collection should be considered for waste fractions for which CRM recycling solutions are available. As new and better CRM recycling schemes become available, collection and sorting that ensure simpler and more complete delivery of relevant waste fractions should be developed.	Source sorting and separate collection of waste fractions with CRM recycling potential could provide simpler and more cost-effective recycling.
B3	Monocell landfilling of CRM-enriched waste that cannot yet be recycled in well-marked locations in the landfill.	CRM-enriched waste, such as industrial slag, dust and sludge for which CRM recovery solutions are not yet available, should be disposed of in a manner that will facilitate later excavation and transport for recycling when new technology makes this possible. This means that relevant waste types are not mixed with other waste, but are landfilled in well-marked monocells. These landfill requirements should be specified as part of the operating permit.	Easier access to raw materials for future CRM recycling operations
B4	Increased security measures to protect temporarily stored CRM recyclable waste from illegal looting of high-value materials and components.	Sorting facilities and waste storage facilities often experience significant challenges with illegal and organized looting of particularly high-value components. These high-value components will often also contain CRMs that are lost for later recycling when stolen. Improved security measures can reduce the size of this problem	Reduced loss of CRM-recyclable components

B5	R&D program to capture CRM in material streams before they end up in recipients from where they cannot be recycled.	Much CRM content is bound in waste streams that are in some cases used as raw materials for the production of cement, glass or other ceramic materials. CRMs that are bound up in low concentrations in cement or other very stable chemical structures will later be very difficult if not impossible to recover. Technical solutions that allow the recovery of CRM from waste streams before these waste streams are used as raw materials for such production processes should therefore be considered.	Potential recycling of CRMs that are otherwise lost in cement and ceramic materials.
B6	R&D program for the development of better sorting technology.	Many waste streams that could have been CRM recycled are lost due to the lack of sorting technology that enables efficient separation from other waste streams. For example, magnets and many batteries are lost due to built-in product design solutions that make sorting difficult. For this reason, there is an urgent need to develop automated sorting solutions for better dismantling of, for example, EE waste and scrapped vehicles. Also for metal alloys, there is a need for better sorting solutions that enable more accurate separation of specific alloys.	Making larger and cleaner waste streams available for CRM recycling
B7	Picking and sorting of components from circuit boards before recycling	Printed circuit boards contain many components with CRM recycling potential, in relatively high concentrations. Today's dominant recycling solutions for printed circuit boards result in the loss of all CRMs except copper and PGM metals. Stripping printed circuit boards of components prior to recycling would allow for much more resource-efficient CRM recycling.	Increased CRM recycling from circuit boards
B8	Sorting magnets for recycling	Magnets are difficult to separate from the products they are part of, partly because they are often mounted in positions in the product that make efficient dismantling difficult, and partly because of the magnetic properties of the materials create a stickiness problem where individual magnets stick together and adhere to metal walls, conveyor belts and other equipment used in sorting. Manual sorting of magnets from WEEE and scrapped vehicles is currently the only option, as functional automatic sorting solutions have not yet been developed, and entails additional costs for sorting facilities that limit this practice. By introducing requirements for mandatory sorting of magnets, as described in Article 28 of the CRMA, this will make a waste stream with a high content of CRMs available for recycling..	Increase magnet recycling, as well as comply with Article 28 of the CRMA.

B9	Industrial sorting system for magnets made of non-magnetic material to avoid stickiness problems.	The magnetic properties of magnets pose challenges in the sorting process as magnets can stick together and adhere to metal walls, conveyor belts and other equipment used in sorting. This challenge can be addressed by demagnetizing the magnets and/or constructing sorting lines for magnets in non-magnetic materials such as brass or aluminum.	Easier and more efficient sorting of magnets
B10	Develop technology to distinguish magnet types	Magnets are made of many different materials, such as AlNiCo, SmCo, NIB and ferritic magnets. If different magnets are mixed, recycling will be difficult.	More resource-efficient recycling of magnetic metals
B11	Sorting of vibrating elements from discarded EE products	Vibration elements in EE products contain tungsten. These components should therefore be separated from discarded EE products and recycled.	Increased tungsten recovery
B12	CRM testing of larger batches of scrap metal delivered to receiving facilities.	More systematic testing of CRM content in collected scrap metal will enable easier and better sorting of specific metal alloys, which in turn will enable more recycling into cleaner and higher-value secondary alloy products.	More efficient resource utilization of CRMs and higher quality of recycled metals
B13	Sorting out aluminum alloys with high magnesium content	When aluminum alloys with a high magnesium content are recycled together with other aluminum alloys, the magnesium content is diluted, increasing the need for new magnesium beyond what would be required by selective recycling of Al-Mg alloys. For this reason, aluminum alloys with a high magnesium content should be collected and recycled in separate processes.	More resource-efficient aluminum recycling
B14	Rationalize the use of metal alloys that facilitate CRM-recycling	More standardized use of fewer aluminum alloys in significant applications, such as beverage cans, will enable aluminum recycling with higher quality secondary metal. Elimination of lead in aluminum materials will minimize heavy metal content in secondary aluminum materials.	Recycling of higher quality aluminum
B15	Labeling of components in EE products containing CRM.	Labelling of CRM-containing components in WEEE will facilitate the sorting of such components for the correct recycling process. The labelling should also entail the publication of the necessary information on material composition in the product passport and on a publicly accessible website in line with Articles 27 and 28 of the CRMA and the Ecodesign Directive	Better sorting of EE components that can be CRM recycled.

B16	Better marking of cables in infrastructure enabling later separation	Cables can contain large amounts of recyclable CRMs. Labeling cables with information about material composition will enable better sorting of specific material fractions from cables that are remediated during infrastructure demolition.	More efficient CRM recovery
B17	Better collection system for cables from demolition projects	Cables can contain large amounts of recyclable CRMs. When buildings and infrastructure are demolished, significant amounts of buried cables are often left behind, and cable waste mixed with other waste fractions is not completely sorted out. More complete and accurate remediation and sorting of cable waste will result in an increased proportion of CRMs in this waste stream being delivered for recycling.	More CRM recycling of cable waste
B18	Development of a process for sorting out gallium (and indium) containing components from discarded displays	Discarded displays contain CRMs, including gallium (and indium), which are expected to be recoverable in the future. Development of a pre-treatment process that enables the sorting and separation of recoverable CRM concentrate from display waste will capture additional feedstock for CRM-recycling.	Better sorting of CRM concentrate from EE waste that can be recycled.
B19	Sorting out heating wires/heating elements	Heating elements in ovens, as well as some types of heating wires, are made of advanced alloys such as rhenium, tungsten (and molybdenum). These should be specifically selected for recycling.	Increased CRM-recycling
B20	More manual dismantling and cutting up of scrap metal and discarded vehicles before shredding	Shredding of scrap metal and end-of-life vehicles is a cost-effective treatment method for large quantities of metal waste, but leads to inadequate separation of individual metals and loss of CRM resources in the fine fraction that occurs during shredding of the waste. Increased manual dismantling and cutting of scrap metal and end-of-life vehicles before shredding will enable better CRM resource utilization, but at the same time be more costly. Stricter requirements for such pre-processing before shredding could improve current practice in this area.	More resource-efficient utilization of CRMs in scrap metal and end-of-life vehicles

B21	Better disassembly of EEE components in discarded vehicles before shredding	Vehicles increasingly contain EE components that are located in many different and often inaccessible places in the vehicles. When scrapping discarded vehicles, only a limited proportion of these EE components are collected before shredding, and increased sorting of these components, can so far only be done through time consuming and costly use of manual labor. A national requirement for more complete sorting of EE components should have the same effect on all shredder plants, and therefore reduce the competitive disadvantages that the additional costs of such practices would entail.	Better CRM recycling of EE waste from scrapped vehicles
B22	Collection scheme for CRM recycling of car glass	Car glass contains small additions of REE and other CRMs to obtain the correct properties, both during use and in the event of a collision. It should be considered whether car glass from scrapped cars should be sorted out and collected for organized recycling back into new car glass or similar applications.	Increased CRM-recycling
B23	Collection of CRM-enriched ammunition remnants from shooting ranges for recycling	Ammunition contains copper, antimony and sometimes bismuth or tungsten. Better collection of ammunition residue from ranges will enable the recovery of these CRMs, while also reducing the leaching of lead and other heavy metals from range sediments.	Increased recycling of copper, antimony, bismuth and tungsten, as well as reduced leaching of lead and other heavy metals.
B24	Organized emptying and dismantling of hand-held fire extinguishers	Hand-held fire extinguishers contain about 6 kg of MAP, monoammonium phosphate. About one million old hand-held fire extinguishers are annually thrown into residual waste or dumped in nature, which leads to loss of the phosphate and inefficient metal recycling, as the attached brass coupling is often not removed before the steel container is recycled. When the steel is directly recycled without mechanical removal of the brass coupling, the steel becomes contaminated. If a deposit scheme of, for example, 500-1000 NOK per extinguisher is established, this could finance a scheme where discarded hand-held fire extinguishers are emptied in a controlled manner, the MAP can be recycled, and the container can either be reused or dismantled for high-quality recycling of steel and brass.	Improved CRM-recycling

B25	Assess the possibility of incineration of selected waste streams in selected waste incineration plants to increase the concentration of CRM-levels in the ash residues.	Ash from waste incineration contains all CRMs, but mostly in concentrations that are too low for recycling to be practical. When mixed waste containing many waste streams is incinerated in the same plant, the CRM levels in waste streams with elevated CRM content will be diluted in the ash by residues from co-incineration with other waste. One possibility that should therefore be considered is the selective incineration of waste with elevated CRM content, such as fines from shredder plants, in dedicated incineration plants that would allow CRM extraction from ash with elevated CRM content. However, such a practice can present process challenges in terms of incineration temperatures and flue gas cleaning. Another example is the incineration of used textiles that cannot be reused. Today, used textiles are mainly exported to Eastern Europe, where 80-90% are sorted out and landfilled. Textiles contain some CRMs from functional fibers and dyes - in addition to high levels of silver.	Ash with elevated CRM content as a basis for recycling.
B26	Expanding the helium return gas scheme	A helium collection system will enable the return of helium that is currently vented to the atmosphere.	Increased helium recycling
B27	Assessing the CRM potential of spent reactor fuel	Spent reactor fuel contains high concentrations of REE and PGM, and after a sufficiently long cooling time are stable compounds. However, the tonnage is low and both technical and political barriers are significant. The prerequisite for being able to extract these is that spent reactor fuel is recycled, as both Finnish and Swedish fuel has been for periods.	Increased CRM-recycling
B28	Analyse wastewater from geothermal power stations for anhydrous CRMs	Water from geothermal plants in Iceland contains elevated levels of inorganic elements, including CRMs. The potential for recovery of CRMs including lithium and boron from these plants should therefore be assessed.	Increased CRM-recycling
B29	Design of vehicles for easier disassembly.	Vehicle design today takes little account of opportunities for efficient disassembly and sorting of components that can be CRM-recycled. Modified product design that enables easier disassembly of car engines for, among other things, the extraction of magnets and circuit boards will provide better sorting of waste streams that can be CRM-recycled. This includes the use of standardized fastening systems and screw heads by model, which has been established for Renault, among others.	Easier and more cost-effective dismantling of scrapped vehicles

B30	Export of tantalum-containing waste to recycling facilities in Estonia	Estonia has a tantalum recycling facility that has the capacity to recycle Nordic tantalum-containing waste, including in the form of certain EE components.	Increased tantalum recovery
B31	Rationalize the use of metal alloys that facilitate CRM recycling	A great many unique metal alloys are used for various products and materials. Increased standardization of a smaller number of alloys for larger applications will simplify the sorting of the alloys and enable more resource-efficient recycling of, among other things, CRMs. It will be particularly important to have restrictions on alloy compositions that make recycling difficult.	More resource-efficient recycling of alloys
B32	Agglomeration of CRM-containing industrial dust enabling recirculation into the melting furnace	Through briquette or pelletization, CRM-enriched dust from primary metal production that would otherwise have to be landfilled can be returned to primary smelting furnaces for further CRM extraction.	Increased CRM-recycling
B33	Information service that provides an overview of available recycling options for CRM-enriched waste.	The European waste industry is complex, which means that scrap metal traders and waste management companies do not necessarily have sufficient knowledge of all available CRM recycling solutions at all times. Lack of knowledge of available recycling solutions can lead to waste that could be CRM-recycled are being sent to other end treatment. An information service that provides an up-to-date and complete overview of available recycling solutions for CRM-enriched waste can therefore contribute to an increased proportion of CRMS waste that can be recycled are being delivered to such treatment.	Can increase the proportion of recyclable CRM-containing waste delivered to recycling facilities.

Better recycling solutions

C1	R&D program for the development of new or more efficient CRM-recycling processes.	Recycling of critical raw materials from many waste streams is not yet possible as the technology to allow this has not yet been developed. For this reason, a massive R&D effort is needed if value chains for secondary production are to be established for all CRMs. Furthermore, the recycling efficiency of many existing CRM recycling processes is very low. For example, current recycling of printed circuit boards results in copper and gold being recycled while dozens of other important CRMs including tantalum, gallium, germanium and PGMs are lost in the slag. Discarded batteries, ammunition residues and fines from grinding scrap metal and EE waste are examples of other CRM-containing waste streams where there is a need to develop better recycling processes.	Available recycling solutions for CRMs and CRM-containing waste streams that currently lack this.
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C2	Description of economic and technical potential for increased CRM recovery in waste management plans for mineral extraction companies.	According to Article 27-1 of the CRMA, companies that extract minerals must prepare a description of the economic and technical potential for increased CRM extraction that the company can contribute to. The description must be submitted to the relevant governmental authority. Companies that can document that they do not handle ore or tailings containing relevant CRM quantities may be granted an exemption from this requirement.	Contribute to identifying opportunities for increased CRM recovery from mineral residues and by-products, and raise awareness among companies of these opportunities, as well as fulfilling Article 27-1 of the CRMA.
C3	R&D program for the development of CRM recovery from wastewater	Industrial and domestic wastewater contains low levels of many CRMs both dissolved and as particles. Although standard sewage and wastewater treatment includes chemical or biological measures to remove some contaminants and nutrients, there are currently few techniques for separating CRMs other than phosphate from wastewater. An R&D program to develop new technological solutions for this, either as a stand-alone treatment step or integrated with existing treatment techniques, could lead to solutions able to capture CRMs that otherwise will be lost.	Increased recycling of CRMs that would otherwise end up as pollution in water recipients.
C4	Assessing the possibility of CRM recovery from zinc processing waste	The CRM recovery potential from waste from Nordic zinc processing is significant, and includes gallium, germanium (and indium). Techniques for such recovery are under development. Jarosite sludge is probably the most relevant waste stream for this, and is available in many millions of tonnes. However, the costs are expected to be significant for the development of such a process, and public support for this work is likely to be needed. In the meantime, a ban on the disposal of jarosite sludge mixed with other wastes that hinder or reduce the potential for future recovery should be considered.	Increased CRM-recycling
C5	Establishment of a Nordic plant for the recovery of zinc and CRM from EAF dust	There are available recovery techniques for EAF dust that enable more efficient CRM recovery than the Waltz furnace process, which is currently the dominant treatment solution for this waste. The establishment of a facility for handling Nordic EAF dust based on best available technology should be considered.	Increased recovery of CRM from EAF dust

C6	CRM recycling of olivine-based slag and foundry sand	CRM recycling of olivine-based slag and foundry sand from the process industry could extract nickel and potentially several other CRMs. Approximately 3 million tonnes of olivine are produced annually in Norway for use as a slag former and foundry sand. This olivine contains 0.4% nickel and 0.03% cobalt, in addition to smaller amounts of other metals. Used foundry sand will also be contaminated with alloying metals from the casting process. Today, foundry sand is either landfilled or used in the concrete industry, where nickel is lost.	Increased CRM-recycling
C7	Investigate the possibility of hydrometallurgical recovery of CRM from slag and other relevant waste streams from pyrometallurgical metal production	Many CRMs are lost in various waste streams from pyrometallurgical processes. The possibility of hydrometallurgical recovery of these CRMs from slag and other relevant waste streams should be investigated.	Increased knowledge about possible recycling processes for CRM-containing waste from pyrometallurgical processes
C8	Develop business models that allows establishment of networks of Nordic steelworks that more clearly specialize in the recycling of specific alloy qualities	Recycling steel with specific alloy recipes in dedicated facilities for this purpose will provide higher resource utilization of CRM alloy components such as manganese, vanadium, niobium and nickel.	More efficient resource utilization of CRMs and higher quality of recycled steel
C9	Develop business models that allow establishment of networks of Nordic secondary aluminum works specializing in the recycling of specific alloy grades	Recycling aluminum with specific alloy recipes in dedicated facilities for this purpose will provide higher resource utilization of CRM alloy components such as magnesium and scandium.	More efficient resource utilization of CRMs and higher quality of recycled aluminum
C10	Increased support for the development of more CRM-efficient process technologies for primary aluminum production	A number of alternative processes for the production of primary aluminium that could result in increased recycling or reduced need for CRMs as feedstocks are under development. Aluminium production using inert anodes would limit the need for graphite in the process, aluminium production with anorthosite would yield pure silica as a by-product, and aluminium production based on a chlorine-based salt melt would eliminate the need for fluorine for the same purpose while also enabling the extraction of trace amounts with CRMs other than aluminium. By supporting the development of these technologies, aluminium production could become far more CRM resource efficient.	Increased recycling of fluorine and graphite, and reduced waste disposal

C11	Development of a recycling process for spent pot liners from primary aluminum production	Development of a recycling process for spent pot liners from primary aluminum production could increase the recovery of fluorine and graphite. The recycling will also result in reduced amounts of hazardous waste for landfilling	Increased recycling of fluorine and graphite, and reduced waste disposal
C12	Recovery of fluorine from electrolysis baths from primary aluminum production	Recycling fluorine from electrolysis baths from the production of primary aluminum will also reduce the waste problem when the same waste has to be landfilled.	Increased recycling of fluoride, and reduced waste disposal
C13	Establishment of a Nordic recycling plant for gallium from industrial wastes from zinc and aluminum production	Establishment of a Nordic plant for the recovery of gallium enriched in dust from primary aluminum production could yield significant quantities of secondary gallium.	Established gallium-recycling
C14	Development of recycling process for circuit boards and other EEE waste that recovers more CRMs	Recycling of WEEE focuses largely on recycling gold and copper, while other CRMs typically end up in the slag. Development of processes that also recycle other CRMs could increase the resource utilization of these waste streams	Increased CRM-recycling
C15	Support the development of a technological process for recycling silicon from solar cells	The amount of waste from solar cell disposal will increase in the coming years. Developing a process for recovering silicon from this waste could recycle high-purity silicon into new products. Solar cells also contain silver, which, although not currently CRM, could soon become one.	Established silicon-recycling
C16	R&D program for developing better material recycling solutions for batteries	Support the development of a technologies that allow recovery of graphite, Co, Li, Ni and Mn from batteries	Better CRM resource utilization when recycling batteries
C17	Development of a process for recycling gallium from discarded LEDs.	LED lighting contains gallium that can potentially be recycled. Development of a recycling process for this will enable more efficient CRM recovery of LED lighting.	Improved CRM-recycling
C18	Assessing the potential for extraction of helium from Norwegian natural gas production	Helium is extracted from natural gas, and world production is dominated by USA and Qatar. Extraction of helium as a new by-product from Nordic natural gas production will strengthen European self-sufficiency in this CRM.	Increased self-sufficiency of helium
C19	Installing additional flotation steps or other additional separation techniques in the ore dressing of CRM-containing minerals	In many cases, it is possible to increase the recovery efficiency of a mineral project by installing additional extraction steps in the beneficiation process. This could enable the recovery of CRMs that are currently lost in the ore dressing processes.	Installing additional flotation stages or other additional separation techniques in the ore dressing process of CRM mines could increase the recovery efficiency of these CRMs.

C20	New ore dressing process with CRM extraction in connection to stabilization pollution from mineral waste	There are a number of historic mine dumps that leak pollution into the environment, in some cases despite measures to limit this pollution. When planning new clean-up measures, it should also be considered whether this can be combined with CRM extraction. One possibility is the recovery of arsenic from certain types of copper mining tailings.	Increased CRM recovery and reduced pollution leaching
C21	Develop business models that enable the restart of closed CRM-recycling facilities	Business models should be developed that enable the restart of Nordic CRM recycling plants that have been shut down due to market manipulation. Examples of such plants are the secondary magnesium production plant on Herøya and the EAF recycling plant in Høyanger in Norway.	Re-establishment of Nordic CRM recycling.
C22	Establishment of a joint Nordic CRM recycling facility for alum slate.	Nordic alum shale constitutes a waste stream that requires expensive and complicated end treatment. At the same time, alum shale contains recoverable CRMs. Establishing a Nordic plant for stabilisation of alum shale combined with CRM extraction would potentially be a business model that both solves a waste problem and at the same time increases CRM recovery.	Increased CRM-recycling
C23	Assess the possibility of utilizing feldspar in mineral residues.	Feldspar is extracted as a by-product from several Nordic mineral projects, including Finnish gold mines, and is being landfilled as these feldspar resources are currently unable to compete with similar products from Turkey. Business models should be sought that enable commercial exploitation of these Nordic feldspar resources.	Increased resource utilization of feldspar from Nordic mineral projects
C24	Establishment of a Nordic value chain for the recycling of beryllium-copper alloys from EE products.	Beryllium-copper alloys are sorted from EE waste due to the toxic properties of beryllium, but there is currently no European recycling capacity for this CRM. The establishment of a Nordic recycling facility for this CRM alloy should therefore be considered. If such a facility comes into operation, a ban on the landfilling of copper-beryllium alloys should be introduced at the same time.	Increased CRM-recycling
C25	Increased R&D efforts for the development of more CRM resource-efficient recycling processes for lead and copper	Theoretically, it is possible to recover several other CRM by-products from copper recovery, including bismuth. Increased R&D efforts could provide technological solutions that further realize this potential.	Increased CRM-recycling

C26	Incentivize copper and nickel mines to extract cobalt more efficiently	There is technical potential for several Nordic copper and nickel mines to increase their production of CRM by-products such as cobalt. This is not profitable at current market prices, but economic incentives could change this situation.	Increased CRM-recycling
C27	Recovery of vanadium from steelmaking slag	A Nordic plant for the recovery of vanadium from steel slag should be established	Increased recovery of vanadium
C28	Recovery of manganese from industrial slag and dust	The Nordic region has a significant manganese processing industry, in addition to many manganese-rich by-product streams. Many of these manganese streams are not suitable for recycling to steelmaking alloys, but could conceivably be recovered for battery purposes through acid leaching.	Increased manganese recovery
C29	Recovery of REE from industrial waste	Nordic mining companies deposit large quantities of REE in flotation sludge and waste gypsum. There is technology with high TRL for their recovery that can be implemented	Increased REE recovery
C30	Extraction of fluoride from mineral residues.	Fluorine can be extracted from several types of Nordic mineral waste, including from Yara's phosphate mine in Silnigara and from apatite separated from LKAB's iron ore.	Increased fluoride recovery
C31	Increased R&D efforts for the development of phosphate recovery from organic waste.	Development of better recycling processes for recycling phosphate from food waste, fishery waste, fertilizer residues, sewage sludge, bioresidues from biogas production and ash residues from biocombustion could increase phosphate recycling	Increased recycling of phosphate from organic waste
C32	Recovery of phosphate from wastewater	Phosphate in wastewater can be precipitated as struvite ($MgNH_4PO_4$) and recycled back to agriculture as fertilizer.	Increased resource efficiency for phosphorus and reduced eutrophication of water recipients.
C33	Recovery of phosphate from bioresidue	Phosphate is recovered from the bioresidue from biogas plants to be used as fertilizer.	Reduced need for extraction of virgin phosphate resources. Better utilization of raw materials for biogas production. Fewer challenges with available distribution area for bioresidue.
C34	Development of technology for the extraction of CRMs from ash residues	Ash residues contain almost all CRMs, although often in low concentrations. Because ash from waste incineration constitute very large volumes, a recovery solution will still be able to extract significant amounts of CRMs such as antimony,	Development of technology for the extraction of CRMs from ash residues

C35	Increased R&D efforts for the development of recycling solutions for CRM from ammunition remnants.	Development of recycling processes for ammunition residues will enable the recycling of, among other things, copper, antimony, bismuth and tungsten from discarded ammunition and collected ammunition residues from firing ranges.	CRM recovery from shooting range.
C36	Increased R&D efforts for the development of recycling solutions for graphite	Development of better recycling processes for recycling graphite from, for example, batteries and industrial furnace linings (SPL) could increase recycling efficiency and profitability in the value chains. Another possibility is the development of production methods for producing battery-quality synthetic graphite from CO ₂ .	Increased graphite recycling
C37	Increased R&D efforts for increased recycling of barite from offshore drilling fluids.	When purifying drilling fluids, weighting material in the form of barite can be used in new offshore drilling operations.	Increased recovery of barite
General measures			
D1	Design of a national plan for increased CRM resource efficiency.	The development of a national plan for increasing CRM resource efficiency is part of the requirements of Article 26 of the CRMA. The plan can be designed as a stand-alone document or incorporated as part of existing national waste plans, and must be revised within five years according to Article 26-2. According to Article 26-3, the programme may include financial incentive schemes such as rebates, cash rewards or refund systems. The plan should define national targets for the recovery of specific CRMs, as well as a description of how the achievement of the targets will be evaluated. Ideally, the plan should take into account that new raw materials are likely to be added to the EU CRM list.	The plan is a requirement of the CRMA and will contribute to increased and more coordinated efforts to increase European resource efficiency for CRMs.
D2	Design of Nordic UNFC database for secondary CRM resources	It should be considered whether the UNFC database for secondary resources being developed in Sweden should be further developed into a Nordic solution.	Better system for recording and evaluating secondary CRM resources

Abbreviations

Al	Aluminium
As	Arsenic
B	Boron
Be	Beryllium
BF	Blast Furnace
BRICS	Brazil, Russia, India, China, South Africa
C	Carbon
CAGR	Compound Annual Growth Rate is a way to measure the average annual growth rate of a market over a period of time.
Ce	Cerium
Co	Cobalt
CRM	Critical Raw Material
CRMA	Critical Raw Material Act
Cu	Copper
DRI	Direct Reduction Plants
Dy	Dysprosium
EAF	Electric Arch Furnace
EEE	Electric and electronic
EEA	European Economic Area
EEC	European Economic Community
EIB	European Investment Bank
ELV	End Of Life Vehicle

EOL-CR:	End Of Life – Collection Rate
EOL-RR:	End Of Life – Recycling Rate
EOL-R	End Of Life – Recovery Rate
EOL-RIR	End Of Life – Recycling Input Rate
EPR	Extended Producer Responsibility
Er	Erbium
Eu	Europium
EV	Electric Vehicle
F	Fluorine
Ga	Gallium
Gd	Gadolinium
Ge	Germanium
He	Helium
Ho	Holmium
HREE	Heavy Rare Earth Elements
ICE	Internal Combustion Engine
Ir	Iridium
La	Lanthanum
LED	Light Emitting Diode
Li	Lithium
LREE	Light Rare Earth Elements
Lu	Lutetium
Mg	Magnesium
Mn	Manganese

Nb	Niobium
Nd	Neodymium
Ni	Nickel
NIB	Neodymium Iron Boron magnet
P	Phosphorous
Pd	Palladium
PCB	Printed Circuit Board
PGM	Platinum Group Elements
ppm	parts per million
Pr	Praesodymium
Pt	Plantinum
Re	Rhenium
REE	Rare Earth Elements
Rh	Rhodium
R, D & I	Research, development and innovation
RSM	Rate of secondary material
Sb	Antimony
SBR	Synthetic Rubber (Styrene-butadiene-rubber)
Sc	Scandium
Si	Silicon
Sm	Samarium
SME	Small and Medium sized Enterprises
STEM	Science, Technology, Engineering and Mathematics
Ta	Tantalum

Tb	Terbium
Ti	Titanium
Tm	Thulium
TRL	Technological Readiness Level
V	Vanadium
W	Tungsten
W2E	Waste to energy
WEEE	Electric and electronic waste
Yb	Ytterbium
Y	Yttrium
Zr	Zirconium

About this publication

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