Nordic Innovation

RECYCLING OF CRITICAL RAW MATERIALS IN THE NORDICS


2023
Sb
Antimony
As
Arsenic
Bauxite
Baryte
Be
Beryllium
Bi
Bismuth
B
Boron
Co
Cobalt
Ga
Gallium
Cu
Copper
Critical CRM level
?% remaining.
Recycle Mode
Close
Manganese
Natural Graphite
Nickel
Niobium
Phosphate rock
P
Phosphorus
PGM
Sc
Scandium
Si
Silicon
Sr
Strontium
Ta
Tantalum
Ti
Titanium
W
Tungsten
V
Vanadium

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Executive summary

A modern society needs access to all critical raw materials (CRM) that are necessary for maintaining and developing its industries, infrastructure and welfare system. CRMs are especially important for many ongoing technology shifts like the Green Deal of EU and digitalization processes. Europe has been facing increasing challenges in meeting its need for these materials, which are defined by their high economic importance and significant supply risk. Currently EU relies heavily on imported supplies of these essential resources.

The Critical Raw Materials Act of EU

The implementation of the Critical Raw Materials Act (CRMA) of EU aims to reduce this vulnerability by establishing a framework to ensure the Union's access to a secure and sustainable supply of critical raw materials. CRMA identifies 53 raw materials that are defined as critical,[1] but this number will likely change in the future when the list is updated. One important measure in this strategy is to increase the selective collection of waste streams that contain CRMs at levels that may be recycled, as stated in Chapter 5. This chapter also states that member states and other countries bound by the EEA Agreement is required to adopt and implement national programmes containing measures designed to increase the collection of waste with high critical raw materials recovery potential and ensure their introduction into the appropriate recycling system within three years after the agreement has entered into force. Within 2030 EU shall have reached a CRM-specific recycling capacity of 25% of its annual consumption of critical raw materials. This is a demanding task, and a successful implementation will require a good understanding of existing opportunities and barriers.

Production of critical raw materials

Almost all critical raw materials are mined as minerals from ores that are a non-renewable resource. But the same raw materials can also be produced as secondary products from recycling of certain waste streams. Strengthening value chains for secondary CRMs will reduce our dependence on virgin raw materials and minimize future supply risks and the environmental footprint of these raw materials. By identifying the products and materials that use CRMs, we can locate the waste streams where these discarded products and materials are found. Important applications for many CRMs include magnets, alloys, catalysts and

1. Some of these CRMs are listed as a group like PGMs and light and heavy REEs.

pigments. Waste streams where such materials or components occur are therefore of interest for potential CRM-recyclers. The review of Nordic waste streams performed as a basis for this report has identified waste with potential for recycling about 900,000 tonnes of CRMs. The quantitively dominant CRMs in this material stream are manganese, phosphate and copper. The waste streams with the largest theoretical recovery potential relative to the recycling targets in CRMA are tailings and waste from metal production.

These waste streams can provide a lot of benefits for the Nordic societies if recovered and used for new products and materials. It would increase circularity, reduce landfilling, provide stable and sustainable workplaces and secure access to raw materials for the downstream processing industries. The Nordic countries have existing industry and expertise that may especially facilitate increased recycling of aluminium, cobalt, copper, fluorspar/fluorine, gallium, rare earth elements, magnesium, manganese, nickel, PGM-metals, phosphate, silicon metal and vanadium.

A profitable and efficient recycling operation requires systems for collection and sorting of waste streams that may serve as feedstock for the recycling operation. There are significant barriers that must be overcome to improve collection, sorting and recycling in ways that make EUs recycling targets for CRMs achievable. Although the concept of circular economy is receiving increased attention, there are still many critical raw materials where the recycling rate is practically zero. This is partly due to high recycling costs compared to the costs of primary production of the same products. But another barrier is the fact that for many critical elements, no mature and cost-effective technologies for sorting and recycling exists. Technological development will eventually lead to more resource- and cost-effective recycling solutions that allow for recycling of more critical raw materials at higher recovery rates. However, this will require time and considerable R&D efforts where the Nordics can play an important part.

Five milestones must be reached to establish Nordic secondary value chains for CRM. These are:

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 recovery of all relevant CRMs at acceptable recovery rates.
5. Market conditions that are economically sustainable for all links in the value chain.

Barriers for better collection and sorting of Nordic CRM-enriched waste

The following barriers are found to restrict more efficient collection and sorting of Nordic CRM-enriched waste in the current situation as of 2023.

- A systematic and complete description of CRM content in relevant waste streams does not exist.
- CRM-enriched waste is landfilled in a way that limits excavation options for recycling purposes.
- Products are designed and assembled in a way that disrupt efficient sorting of CRM-enriched materials.
- Buildings and infrastructure are constructed in a way that make extraction of CRM-rich components during decommissioning difficult.
- CRM-enriched waste streams are lost in cement and ceramic materials.
- CRMs are lost in waste water.
- Non harmonized standards for collection and sorting between different municipalities and regions.
- No governmental incentives or requirements for collection of CRM-rich waste streams.
- EPR-schemes only partly separate CRM-materials for recycling.
- Some sectors are not included in collection and recycling schemes.
- Some EPR schemes refuse CRM-enriched waste that could have been recycled.
- Challenges with increasing number of sorted waste streams.
- Much collected CRM-enriched waste is not delivered to recycling.
- No robust and flexible technology for advanced automated sorting and defragmentation of WEEE and other important CRM-enriched waste is available yet.
- Magnets are difficult to separate from other materials.
- European recycling industries loses much CRM-enriched material through questionable export mechanisms.
- Biodegradable waste is incinerated instead of used for production of biogas.
- Loss of CRM in spent drilling fluids.
- Conflict with existing regulation that limits CRM-recycling options.

Barriers for better recycling of CRMs

The following barriers are found to restrict Nordic CRM-recycling.

- Many CRMs are distributed in products and materials at low levels that make recycling challenging.
- Substitution with less valuable materials and micronization of components with increasingly heterogeneous chemical composition makes recycling less profitable.
- Large amounts of CRMs are lost during metal recycling.
- No recycling technology is available for CRM-recycling from multiple feedstocks.
- CRM-recycling is often less cost-effective than production of virgin CRMs.
- Small volumes and large fluctuations in prices make CRM-recycling economically challenging.
- Market manipulations from dominant CRM-suppliers disrupt European CRM-recycling.
- NIMBY-responses blocks new CRM-recycling projects or necessary support infrastructure.

Measures and instruments for increased CRM-recycling

The following measures should be considered as instruments to reach the milestones necessary for increasing Nordic CRM-recycling.

Measures for systematic identification of waste streams with CRM-recycling potential:

- National program for mapping CRM-levels in relevant waste streams.
- National statistic accounting of significant CRM material streams showing both consumptions, collected waste and recycled CRM-volumes.
- Put on market demands for product design that support efficient identification and separation of CRM-enriched components and materials.
- Design and construction of buildings and infrastructure that support easy identification and separation of CRM-rich materials during future decommissioning.

Measures for better collection of waste streams with CRM-recycling potential:

- Separate collection and delivery of CRM-enriched waste for recycling.
- Landfill bans on recyclable CRM enriched waste.
- Mono-cell landfilling of CMR-enriched waste that cannot yet be recycled at well-marked locations in the landfill.
- Mapping of available CRM-materials for recycling as part of all decommissioning and demolition projects.
- Recovery of CRM from wastewater.
- Consider EPR-scheme for non-WEEE CRM-enriched waste streams.
- Upgrading EPR-scheme for waste regarding CRMs for WEEE, vehicles and tyres.
- CRM-recycling obligation for sectors that are omitted from EPR-schemes.
- Increased security measures to guard against illegal looting of high value materials in WEEE.
- R&D program for capturing CRM material streams before ending up in unrecoverable recipients.
- Collection of CRM-enriched ammunition residues from shooting ranges.
- Requirements or economic incentives for delivery of CRM-enriched waste to facilities that can recycle it.

Measures for better separation of CRM-enriched materials from other materials in the waste stream:

- Removal and sorting of components from printed circuit boards before recycling.
- Incineration of selected waste streams in different W2E-plants that allow for enhanced CRM-levels in ashes.
- R&D program for development of better sorting technology.
- Mandatory sorting of magnets.
- Industrial sorting system for magnets constructed by non-magnetic material to avoid stickiness problem.
- CRM-recycling obligation for sectors that are omitted from EPR-schemes.
- Consider EPR-scheme for non-WEEE CRM-enriched waste streams.
- Upgrading EPR-scheme for waste regarding CRMs for WEEE, vehicles and tyres.

Measures that support development of recycling technologies that allow for recovery of relevant CRMs at acceptable recovery rates:

- R&D program for development of new or more efficient CRM-recycling processes.
- Program that monitors progress towards specific recycling targets for critical elements.
- State investment fund that supports the establishment of new CRM recycling.
- National CRM-stock pile program that buy secondary CRM-products at regulated prices.

Measures for creation of market conditions that are economically sustainable for all links in the value chains for secondary CRMs:

- State guarantee for recycling facilities.
- State investment fund that supports the establishment of new CRM recycling.
- National CRM-stock pile program that buy secondary CRM-products at regulated prices.
- Information service that provides an overview of available recycling options for CRM-enriched waste.
- Minimum requirements for recycling efficiency when delivering CRM-enriched waste to recycling.
- Mandatory reporting of recycled secondary CRM from recycler.
- Program that monitors progress towards specific recycling targets for critical elements.
- Updating national regulations that restricts CRM-recycling.

Sammendrag (Norsk)

Et moderne samfunn trenger tilgang til en rekke kritiske råvarer (CRM) som er nødvendige for å opprettholde og utvikle egen industri, infrastruktur og velferdsordninger. CRM-er er spesielt viktige for mange pågående teknologiskifter som EUs Green Deal og digitaliseringsprosesser. Europa har i senere år opplevd økende utfordringer når det gjelder å dekke sitt behov for slike materialer som defineres ved sin store økonomiske betydning og betydelige forsyningsrisiko. EU er per 2023 er sterkt avhengig av import for å dekke sitt CRM-behov.

EUs rettsakt for kritiske råmaterialer

Innføringen av Critical Raw Materials Act (CRMA) i EU har som mål å redusere denne sårbarheten ved å etablere et rammeverk som styrker Unionens tilgang til en sikker og bærekraftig forsyning av kritiske råmaterialer. CRMA identifiserer 53 råvarer som er definert som kritiske, men dette tallet vil sannsynligvis endre seg i fremtiden når listen oppdateres. Et viktig tiltak som beskrives i kapittel 5 i CRMA er å øke den selektive innsamlingen av avfall som inneholder CRM-er på et nivå som kan resirkuleres. Samme kapittel slår fast at medlemsland og land bundet av EØS-avtalen er pålagt å etablere nasjonale programmer som inneholder tiltak utformet for å økt innsamling av avfall med høyt CRM-gjenvinningspotensiale og som sikrer at dette avfallet ledes til et velfungerende gjenvinningssystem innen tre år etter at avtalen har tredd i kraft. Innen 2030 skal EU ha nådd en CRM-spesifikk resirkuleringskapasitet på 25 % av sitt årlige forbruk av kritiske råmaterialer. Dette er en krevende oppgave, og en vellykket implementering vil kreve god forståelse for eksisterende muligheter og barrierer.

Produksjon av kritiske råmaterialer

Nesten alle kritiske råmaterialer utvinnes som mineraler fra malmer som er en ikke-fornybar ressurs. Men de samme råmaterialene kan også produseres som sekundærprodukter fra resirkulering av visse avfallsstrømmer. Styrking av verdikjeder for sekundære CRM-er vil redusere vår avhengighet av jomfruelige råvarer, redusere fremtidig forsyningsrisiko og det miljømessige fotavtrykket til disse råmaterialene. Ved å forstå hvilke produkter og materialer som CRM-er brukes i kan avfallsstrømmer der disse kasserte produktene og materialene forekommer identifiseres. Viktige bruksområder for mange CRM-er inkluderer magneter, legeringer, katalysatorer og pigmenter, og avfallsstrømmer der slike materialer eller komponenter forekommer er derfor av interesse for potensielle CRM-gjenvinnere. En gjennomgang av nordiske avfallsstrømmer har identifisert avfall med potensial for resirkulering av om lag 900 000 tonn CRM. De kvantitativt dominerende CRM-ene i denne materialstrømmen er mangan, fosfat og kobber. Avfallsstrømmene med det største teoretiske gjenvinningspotensialet i forhold til resirkuleringsmålene i CRMA er avgangsmasser og avfall fra metallproduksjon.

Hvis CRM fra disse avfallsstrømmene gjenvinnes kan dette gi mange fordeler for de nordiske samfunnene, blant annet økt sirkularitet, redusert avfallsdeponering, stabile og bærekraftige arbeidsplasser samt sikker tilgang til råvarer for nedstrøms prosessindustri. De nordiske landene har eksisterende industri og kompetanse som spesielt kan legge til rette for økt resirkulering av aluminium, kobolt, kobber, flusspat/fluor, gallium, sjeldne jordartsmetaller, magnesium, mangan, nikkel, PGM-metaller, fosfat, silisiummetall og vanadium.

En lønnsom og effektiv gjenvinningsvirksomhet krever systemer for innsamling og sortering av avfallsstrømmer som kan tjene som råstoff for gjenvinningsvirksomheten. Det er betydelige barrierer som må overvinnes for å forbedre innsamling, sortering og resirkulering på måter som gjør EUs resirkuleringsmål for CRM-er oppnåelige. Selv om konseptet sirkulær økonomi får mye oppmerksomhet, er det fortsatt mange kritiske råvarer hvor gjenvinningsgraden praktisk talt er null. Dette skyldes blant annet høye gjenvinningskostnader sammenlignet med kostnadene ved primærproduksjon av de samme produktene. En annen barriere er det faktum at det for mange kritiske råmaterialer ikke finnes modne og kostnadseffektive teknologier for sortering og resirkulering. Teknologisk utvikling vil på sikt føre til mer ressurs- og kostnadseffektive gjenvinningsløsninger som gir mulighet for resirkulering av mer kritiske råvarer til høyere gjenvinningsgrader. Dette vil imidlertid kreve tid og betydelig FoU-innsats.

Etableringen av nordiske sekundære verdikjeder for CRM vil kreve realisering av fem milepæler. Disse er:

1. Et system som gjør det mulig å identifisere avfallsstrømmer med CRM-resirkuleringspotensial.
2. Et system for kostnadseffektiv innsamling av avfallsstrømmer med CRM-resirkuleringspotensial.
3. Et system for å skille materialer anriket med CRM fra andre materialer i avfallsstrømmen.
4. En resirkuleringsteknologi som muliggjør gjenvinning av alle relevante CRM-er med akseptabel resirkuleringsgrad.
5. Markedsforhold som er økonomisk bærekraftige for alle ledd i verdikjeden.

Barrierer for bedre innsamling og sortering av nordisk CRM-anriket avfall

Følgende barrierer er funnet å begrense mer effektiv innsamling og sortering av nordisk CRM-anriket avfall i dagens situasjon fra og med 2023.

- En systematisk og fullstendig beskrivelse av CRM-innhold i relevante avfallsstrømmer eksisterer foreløpig ikke.
- CRM-anriket avfall deponeres på måter som begrenser fremtidig uthenting til gjenvinningsformål.
- Produkter er designet og satt sammen på måter som begrenser mulighetene for effektiv separasjon og utsortering av CRM-anrikede materialer og komponenter.
- Bygninger og infrastruktur er konstruert på måter som gjør utvinning av CRM-rike komponenter og materialer under riving vanskelig.
- CRM-anrikede avfallsstrømmer går tapt i sement og keramiske materialer.
- CRM-er går tapt i avløpsvann.
- Ikke-harmoniserte standarder for innsamling og sortering av avfall mellom ulike kommuner og regioner.
- Ingen statlige insentiver eller krav til innsamling av CRM-rike avfallsstrømmer.
- Eksisterende produsentansvarsordninger sorterer bare delvis ut CRM-materialer for resirkulering.
- Enkelte sektorer er ikke inkludert i eksisterende innsamlings- og gjenvinningsordninger.
- Noen produsentansvarsordninger avviser CRM-anriket avfall som kunne vært resirkulert.
- Utfordringer med økende antall sorterte avfallsstrømmer.
- Mye innsamlet CRM-anriket avfall leveres ikke til resirkulering.
- En robust og fleksibel teknologi for avansert automatisert sortering og defragmentering av EE-avfall og annet viktig CRM-anriket avfall finnes ennå ikke.
- Magneter er vanskelige å skille fra andre materialer.
- Europeisk gjenvinningsindustri mister mye CRM-anriket materiale gjennom tvilsomme eksportmekanismer.
- Biologisk nedbrytbart avfall forbrennes i stedet for å brukes til produksjon av biogass.
- Tap av CRM i brukte borevæsker.
- Konflikt med eksisterende regulering som begrenser alternativer for CRM-resirkulering.

Barrierer for bedre resirkulering av CRM

Følgende barrierer vurderes å begrense nordisk CRM-resirkulering.

- Mange CRM-er distribuert i produkter og materialer i lave konsentrasjoner som gjør resirkulering utfordrende.
- Substitusjon med mindre verdifulle materialer og mikronisering av komponenter med stadig mer heterogen kjemisk sammensetning gjør resirkulering mindre lønnsomt.
- Store mengder CRM går tapt under gjenvinning av metall.
- Ingen resirkuleringsteknologi tilgjengelig for CRM-resirkulering fra flere avfallsstrømmer.
- CRM-resirkulering er ofte mindre kostnadseffektivt enn produksjon av jomfruelig CRM.
- Små volumer og store svingninger i prisene gjør resirkulering av mange CRM-er økonomisk utfordrende.
- Markedsmanipulasjoner fra dominerende CRM-leverandør-land forstyrrer europeisk CRM-resirkulering.
- NIMBY-reaksjoner blokkerer nye CRM-resirkuleringsprosjekter eller nødvendig støtteinfrastruktur.

Tiltak og virkemidler for økt CRM-resirkulering

Følgende tiltak bør vurderes som virkemidler for å nå milepælene som er nødvendige for å øke nordisk CRM-resirkulering.

Tiltak for systematisk identifisering av avfallsstrømmer med CRM-resirkuleringspotensial:

- Nasjonalt program for kartlegging av CRM-nivåer i relevante avfallsstrømmer.
- Nasjonalt statistikkregnskap som bokfører betydelige CRM-materialstrømmer med både forbruk, innsamlet avfall og resirkulerte CRM-volumer.
- Stille markedskrav til produktdesign som støtter effektiv identifikasjon og utsortering av CRM-anrikede komponenter og materialer.
- Design og konstruksjon av bygninger og infrastruktur som støtter enkel identifikasjon og separering av CRM-rike materialer ved fremtidig rivning.

Tiltak for bedre innsamling av avfallsstrømmer med CRM-gjenvinningspotensial:

- Separat innsamling og levering av CRM-anriket avfall til relevante gjenvinningsanlegg.
- Deponiforbud for resirkulerbart CRM-anriket avfall.
- Monocelle deponering av CMR-anriket avfall som ennå ikke kan resirkuleres på godt merkede steder i deponiet.
- Kartlegging av tilgjengelige CRM-materialer for resirkulering som del av alle større rivingsprosjekter.
- Gjenvinning av CRM fra avløpsvann.
- Vurdere produsentansvarsordninger for CRM-anrikede avfallsstrømmer som ikke er WEEE.
- Oppgradering av produsentansvarsordninger for WEEE, kjøretøy og dekk når det gjelder CRM-anriket avfall.
- CRM-gjenvinningsplikt for sektorer som er utelatt fra eksisterende produsentansvarsordninger.
- Økte sikkerhetstiltak for å beskytte mellomlagret CRM-anriket avfall mot ulovlig plyndring av materialer og komponenter med høy verdi.
- FoU-program for å fange CRM-materialstrømmer før de ender opp i resipienter fra hvor de ikke kan gjenvinnes.
- Innsamling av CRM-anrikede ammunisjonsrester fra skytebaner.
- Krav om eller økonomiske insentiver for levering av CRM-anriket avfall til anlegg som kan resirkulere CRM-innholdet.

Tiltak for bedre separering av CRM-anrikede materialer fra andre materialer i avfallsstrømmen:

- Avplukking og utsortering av komponenter fra kretskort før resirkulering.
- Forbrenning av utvalgte avfallsstrømmer i ulike avfallsforbrenningsanlegg for oppkonsentrering av CRM-nivåer i askerestene.
- FoU-program for utvikling av bedre sorteringsteknologi.
- Obligatorisk sortering av magneter.
- Industrielt sorteringssystem for magneter laget av ikke-magnetisk materiale for å unngå sammen-klistrings-problemer.
- CRM-resirkuleringsplikt for sektorer som er utelatt fra eksisterende produsentansvarsordninger.
- Vurder produsentansvarsordning for CRM-anrikede avfallsstrømmer som ikke er WEEE.
- Oppgradering av produsentansvarsordninger for WEEE, kjøretøy og dekk når det gjelder CRM-anriket avfall.

Resirkuleringsteknologi som muliggjør gjenvinning av alle relevante CRM-er med akseptabel resirkuleringsgrad:

- FoU-program for utvikling av nye eller mer effektive CRM-gjenvinningsprosesser.
- Program som overvåker fremdriften i forhold til spesifikke resirkuleringsmål for CRM-er.
- Statlig investeringsfond som støtter etablering av ny CRM-gjenvinning.
- Strategisk CRM-lagerprogram som kjøper inn sekundære CRM-produkter til regulerte priser.

Tiltak for å skape markedsforhold som er økonomisk bærekraftig for alle ledd i verdikjedene for sekundære CRMer:

- Statsgaranti for gjenvinningsanlegg.
- Statlig investeringsfond som støtter etablering av ny CRM-gjenvinning.
- Strategisk CRM-lagerprogram som kjøper sekundære CRM-produkter til regulerte priser.
- Informasjonstjeneste som gir oversikt over tilgjengelige resirkuleringsmuligheter for CRM-anriket avfall.
- Minimumskrav til gjenvinningsgrad ved levering av CRM-anriket avfall til resirkulering.
- Obligatorisk rapportering av andel resirkulert CRM fra gjenvinningsanlegg.
- Oppdatere nasjonale forskrifter som begrenser CRM-resirkulering.

1. Introduction

1.1 Scope of work

A modern society needs access to all critical raw materials (CRM) that are necessary for maintaining and developing its industries, infrastructure and welfare system. CRMs are especially important for many ongoing technology shifts like the Green Deal of EU and digitalization processes. Europe has been facing increasing challenges in meeting its need for these materials, which are defined by their high economic importance and significant supply risk. Currently, EU relies heavily on imported supplies of these essential resources.

The implementation of the Critical Raw Materials Act (CRMA) of EU aims to reduce this vulnerability by establishing a framework to ensure the Union's access to a secure and sustainable supply of critical raw materials. One important measure in the Act is to increase the selective collection of waste streams that contain CRMs at levels that may be recycled, as stated in Chapter 5. This chapter states that member states and other countries bound by the EEA Agreement is required to adopt and implement national programmes containing measures designed to increase the collection of waste with high critical raw materials recovery potential and ensure their introduction into the appropriate recycling system within three years after the agreement has entered into force. A formal approval of the act in its current form means that within 2030 EU shall have reached a CRM-specific recycling capacity of 25% of its annual consumption of strategic raw materials. This is a demanding task, and a successful implementation will require a good understanding of existing opportunities and barriers.

Through the project, *Recycling of Critical Raw Materials in the Nordics*, the Nordic region has taken a common approach to how these issues should best understood and addressed. This report answers a call from the Nordic Working Group on Circular Economy (NCE) of the Nordic Council of Ministers for a description of potential actions the Nordic region can take to increase collection for recycling of waste that is rich in critical raw materials (CRMs), in line with the Critical Raw Materials Act, as well as measures to ensure these resources are sorted and recycled within the Nordic region.

An important issue for this project is to identify and describe advantages specific to the Nordic countries when it comes to recycling of CRMs based on available waste streams, industry and technology, together with skills and competence in the Nordic work force that may result in projects that can help the Nordic region lead the way when it comes to increased CRM-recycling.

This report describes obstacles linked to policies, business models, technologies and other factors, along with opportunities and recommendations for decision-makers. An overview of areas for further study will be provided based on identified obstacles and opportunities.

1.1.1 Methodology

This report is written based on publicly available information that are referenced throughout the document. The report quantifies Nordic overall waste streams at a national level that may contain CRMs and singles out selected sub streams of waste that are expected to contain recoverable levels of CRMs. The amounts of CRMs that can be theoretically recovered is estimated. Nordic overall main waste streams are quantified based on data from Eurostat and described based on Eurostat guidelines.[2]

Quantification of waste streams with recoverable CRMs

Based on a review of available documentation on Nordic waste streams a selection of waste sub-streams that is expected to contain recoverable levels of CRMs have been quantified. The theoretical recovery potential of individual CRMs from each sub stream of waste have been calculated based on the size[3] of the waste stream and reported CRM-concentrations in the respective waste stream.[4] The estimation of the CRM amounts in the selected waste streams is based on limited data and are therefore associated with significant uncertainty. In selecting data, newer data have naturally been preferred over older data. Where both IPC analysis and XRF data are available, IPC-data have been preferred. XRF data is only used where IPC data are not available. For some waste streams with known presence of specific CRMs, but where applied chemical analysis method has too high detection limits to register actual levels, half of the detection limit has been used for calculation of the CRM-content in the waste stream. The share of CRMs accounted for through this calculation mechanism on the total CRM estimates is limited. Most data are based on reported information in peer reviewed publications. In a few cases where this is not available, information from private companies that has been authorised for use but not publicized has been included.

Waste streams that are considered to contain recoverable levels of CRMs include post-consumer waste from specific EPR sectors such as printed circuit boards from WEEE, batteries and waste tires together with residues from current recycling infrastructure, such as shredder fluff and the ashes from waste incineration. Ashes from combustion of biomass have also been included, as the chemical composition is quite similar to ashes from waste incineration. From the minerals sector, tailings

2. Eurostat. 2010. Guidance on classification of waste according to EWC-Stat categories
3. Overall tonnage of each waste stream has been based on best available and newest available sources. For some of the waste streams, such as mining waste and certain industrial byproduct, volumes might change a lot from year to year. In these cases, we have estimated an average year based on several years of data.
4. The theoretical recovery potential assumes a 100% recovery rate which is unrealistic for almost all existing recycling processes but provides a comparable estimation of the upper limit for future recycling processes.

from operating mines, and dusts and slags from mineral processing and smelter industries has been included. Annually landfilled alum shale is also included. Additional information about these waste streams and associated database can be found in Appendix 3 of this report.

Only waste streams from ongoing industrial operations are included in this report. Legacy issues like landfilled waste, old tailings disposals etc from centuries of earlier production are not part of the calculation of the Nordic CRM-recycling potential in this report. Many smaller enterprises and niche productions are also excluded, due to time constraints of this project. These issues may be examined at a later stage.

Inclusion of waste data from autonomous regions, territories and special law areas of the Nordics

Based on available information the following assumptions have been made about waste streams from the autonomous regions, territories, and special law areas of the Nordics.

Åland (Finland) seems to have no processing industry of relevance for CRM-recovery, and all WEEE and MSW is assumed to be disposed of in mainland Finland. Hence, the numbers are included in mainland Finland. Some of the archipelago has alum shale, but no data on deliveries to landfills have been found. The bioash from Åland is assumed to have same elemental composition as Finland.

It is assumed that all waste from Christiansø (Denmark) is delivered to waste treatment in Denmark or Sweden and therefore included in waste accounts from these countries.

Greenland (Denmark) is included with figures for MSWI and WEEE numbers. Mining wastes are low, as only one small mineral mine is active, the many earlier mines have all closed and are hence not included.

Faeroy Islands (Denmark) is included with figures for MSWI and WEEE numbers.

Svalbard, Bjørnøya and Jan Mayen (Norway) has no processing industry and send all waste to mainland Norway (Tromsø). Current Norwegian operating coal mine is set to close, and the coal fired CHP station has been converted to diesel. Russian settlement at Svalbard do not have any significant processing industry.

Calculation of Nordic CRM market volumes

The size of the global CRM-markets is calculated based on updated USGS global primary production figures if available. As there are no reliable public statistics regarding recycling grades for metals and elements, secondary production has been estimated by the authors. The sum of primary production and secondary production adds up to the total market volume.

Critical Raw Materials enters the Nordic countries from own production, imported raw materials and semi-finished products and end products – such as computers, cars and phones.

CRMA is mandating specific recycling targets for CRMs as a percentage, but these targets have not yet been fixed as an actual tonnage presented to the market. To bridge this information, it is assumed that the Nordic countries consume an amount of the global CRM production equal to the Nordic GDP share of global GDP. For 2022, the Nordic GDP was 1,76% of global GDP. Hence it is assumed that the Nordic consumption of individual CRMs is 1,76% of the global consumption of the same CRM. Calculations of Nordic CRM recovery and recycling shares are based on this baseline.

1.2 What are critical raw materials (CRM) and why are they important?

All products consumed by a human society are constructed from a limited source of raw materials, many with unique chemical and physical properties that serve specific needs and applications. These raw materials are elements or chemical compounds that differs widely both regarding its natural abundance and economical importance. While iron and oxygen are examples of abundant raw materials that are easily accessible for extraction in large quantities, rhodium, palladium and platinum are examples of raw materials that are much scarcer and make up only a few parts per billion of the earth's crust.

An increasing number of technologies and services in a modern society depend on raw materials that are becoming more and more scarce.If the needs for these raw materials no longer can be met, industry that uses them may come to a halt, and important social functions that depend on them may be restricted or collapse. Shortage of raw materials will typically lead to further supply failures downstream in their value chains as a shortage of components or finished products. Examples of critical raw materials include phosphorus in the form of phosphate (necessary for all plant growth and food production), lithium (necessary for battery production), gallium (necessary for the production of LED light) and rare earth metals (necessary for electrical products and permanent magnets). Figure 1.1 summarizes chemical concepts used to describe raw materials. Raw materials are sometimes referred to as elements if they are pure substances that cannot be broken down into other chemical substances, or metals if they belong to this sub-group of chemical elements. Raw materials extracted from geological ores are often referred to as minerals, while all homogenous substances with a fixed chemical composition, including elements, can be referred to as chemical compounds, or alloys if the chemical compounds are purely metallic. All raw materials are chemical compounds, but chemical compounds without any applications are not considered raw materials as illustrated by Figure 1.1.

What is the difference between raw materials, chemical elements, compounds and minerals?

All raw materials consist of chemical elements or combinations of elements called compounds. The raw material feldspar for instance has a chemical composition that consists of six elements that includes aluminium and silicon. Most raw materials, like feldspar are extracted as minerals from earths crust. Some chemical elements are metals. A chemical compound of several metals is called an alloy. Although almost all raw materials are extracted as minerals, not all minerals have applications that make them considered a raw material. Minerals or chemical compounds with little or no use, that are for some reason handled by humans, are often referred to as waste.

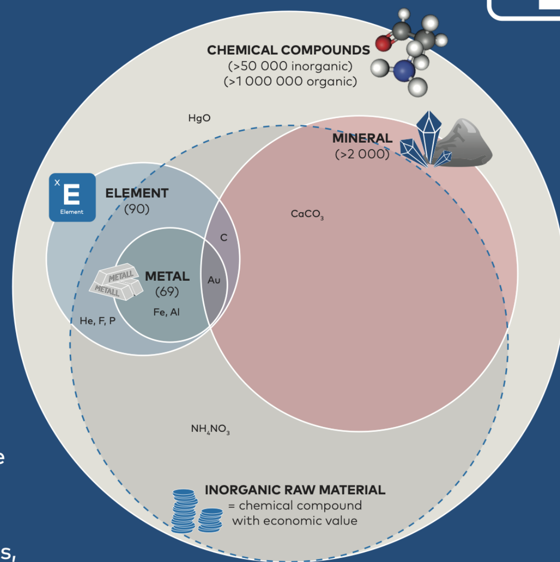

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Figure 1.1 Chemical concepts used to describe raw materials.
Illustration Bergfald Miljørådgivere.

Growing populations and economies increase the pressure on remaining geological reserves of elements with already limited availability. In addition, there are technological changes such as digital- and green transitions, which require further increased supply of many of the same raw materials. Taken together, these trends are expected to lead to higher levels of consumption of many critical raw materials in the order of 10–100 times in the coming years compared to the global consumption today. These trends are confirmed independently by several international expert groups that have analysed this situation in separate studies including OECD,[5] UNEP IRP[6] and IEA.[7]

This situation would be challenging in the best of times and is aggravated by an increasing number of international and global crises that are disrupting already strained supply chains. The COVID-19 epidemy and the increasing number of military conflicts has already led to significant disruptions in European CRM-supply chains, for example of manganese. Escalations of these conflicts may cause further disruptions. On top of this comes the climate crisis that is already destabilizing national economies and governments due to rising temperatures, more extreme weather, and forest fires.

5. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences, OECD 2019
6. Global Resources Outlook 2019: Natural Resources for the Future We Want, United Nations Environment Programme International Resource Panel
7. The Role of Critical Minerals in Clean Energy Transitions, International Energy Agency (IEA) 2021

The combination of already strained supply lines for critical raw materials and an increasing number of crises and conflicts has understandably led to higher political attention towards supply risks for important raw materials, and many states and major powers, including the EU have developed strategies to reduce these supply risks. These strategies often include lists that specify which raw materials that are considered to be of especially high concern. How these raw materials are defined, and which raw materials that are included in these lists varies between different states. Figure 1.2 presents an overview of chemical elements and compounds that are listed as critical raw materials by different powers as of December 2023.

RAW MATERIAL	EU (2023)	USA (2023)	CANADA (2023)	AUSTRALIA (2023)	JAPAN (2021)	SOUTH-KOREA (2023)	BRAZIL (2021)	RUSSIA (2022)	INDIA (2023)	CHINA (2016)	SOUTH-AFRICA (2022)
Aluminum	!	!	!			!					
Aluminum oxide, high-purity				!							
Antimony	!	!	!	!	!	!		!	!	!	
Arsenic	!	!									
Baryte/Barium	!	!			!						
Bauxite	!							!		!	
Beryllium	!	!		!	!			!	!		
Bismuth	!	!	!	!	!	!			!		
Boron	!				!						
Cadmium									!		
Potassium			!				!	!	!	!	
Cesium		!	!		!			!			
Chromium		!	!	!	!	!		!		!	!
Cobalt	!	!	!	!	!	!	!	!	!	!	!
Coking Coal	!				!						!
Copper	!	!	!			!	!	!		!	!
Electrolytic steel		!									
Feldspar	!										
Fluorspar	!	!	!		!			!		!	
Gallium	!	!	!	!	!			!	!		
Germanium	!	!	!	!	!			!	!		
Gold								!		!	
Hafnium	!	!		!	!			!	!		
Helium	!		!	!				!			
HREE	!	!	!	!	!	!	!	!	!	!	!
Indium		!	!	!	!	!		!	!		
Iron ore										!	!
Lead								!			!
Lithium	!	!	!	!	!	!	!	!	!	!	!
LREE	!	!	!	!	!	!	!	!	!	!	!
Magnesium	!	!	!	!	!						
Manganese	!		!	!	!	!		!			!
Molybdenum			!		!	!	!	!	!	!	
Natural Graphite	!	!	!	!		!	!	!	!	!	
Nickel	!	!	!		!	!	!	!	!	!	!
Niobium	!	!	!	!	!	!	!	!	!		
PGM	!	!	!	!	!	!	!	!	!		!
Phosphate rock	!						!		!	!	
Phosphorus, wh.	!									!	
Rhenium				!				!	!		
Rubidium		!			!			!			
Scandium	!	!	!	!				!			
Selenium					!	!		!	!		
Silicon carbide		!									
Silicon, metal	!	!		!	!	!	!	!	!		
Silver								!			
Strontium	!				!	!			!		
Sulfur							!				
Tantalum	!	!	!	!	!	!	!	!	!		
Tellurium		!	!		!						
Thallium					!		!				
Tin		!	!			!	!	!		!	
Titanium, metal	!	!	!	!	!	!	!	!	!		
Tungsten	!	!	!	!	!	!	!	!	!	!	
Uranium			!				!	!		!	!
Vanadium	!		!	!	!	!	!		!		!
Zinc		!	!			!		!			!
Zirconium		!		!	!	!		!	!	!	

Figure 1.2 Chemical elements and compounds that are listed as critical raw materials by different powers as of December 2023. Illustration Bergfald Miljørådgivere.

Raw materials that are listed as critical are subject to special measures that are aiming to strengthen the value chains that supplies these raw materials. A description of EU policies regarding critical raw materials are given in section 1.5.

1.3 Markets and value chains for critical raw materials

Virtually all of the 90 chemical elements found in the Earth’s crust have applications as raw material in the production of various goods and services in a modern society, some more than others. Some elements are used as pure substances like carbon (graphite or coke) or helium, but most elements are used as part of a chemical compound that may be part of materials like alloys or ceramics. For several elements with a large global consumption, a worryingly small known remaining geological reserve exist. In addition, many elements are unevenly distributed on the Earth's surface. Some are only readily available for extraction in countries with unstable or protectionist governance regimes that may represent an additional significant supply risk. In addition, for many critical raw materials no recycling options exists yet, and all inherent CRM in discarded products are therefore currently lost as waste.

The global market for critical raw materials is huge both in terms of economic value and quantities that are traded. The total quantity of individual CRMs (as defined by EU) that are annually consumed on a global scale varies greatly however, as illustrated in figure 1.3.

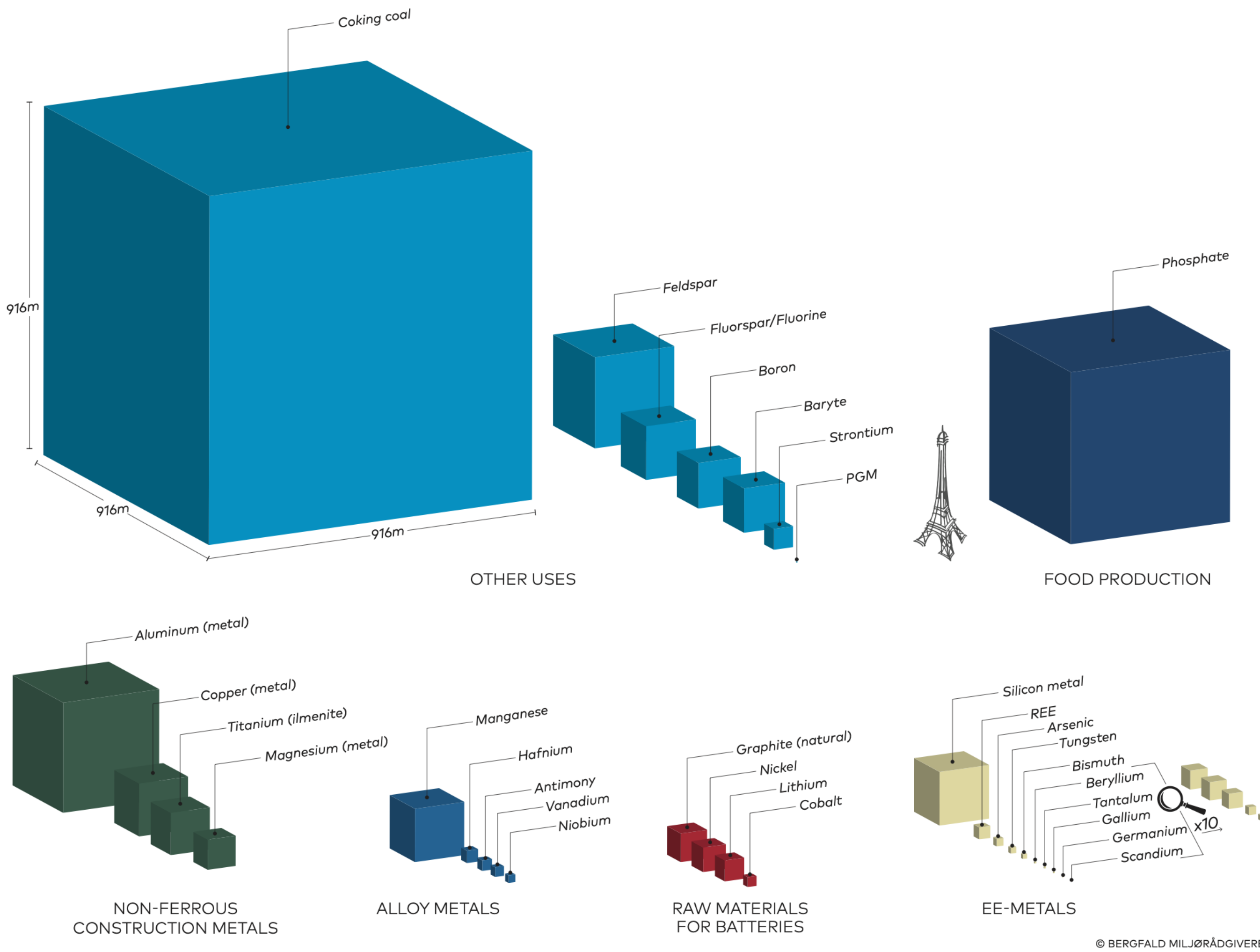


Figure 1.3 Total quantity of critical raw materials put on the global market every year. Helium is a gas and is not included in the illustration. The illustration is based on public available market data of production volumes for individual CRMs per 2023.
Illustration Bergfald Miljørådgivere.

Many critical elements occur in the Earth's crust at very low levels or are for other reasons difficult to find in ores that lend itself to cost-effective extraction. This creates great pressure on extractable resources and leads to high vulnerability for future supply chains that rely on these elements as raw material, making it urgent to establish circular value chains that create closed technical loops where raw materials are recycled from one product life to the next. A closed technical loop for a CRM requires effective recycling processes. For many CRMs necessary technologies for this kind of recycling has yet to be developed. Examples of CRMs without available post-consumer recycling technologies as of 2023 include gallium, germanium, hafnium and niobium.

1.3.1 Value chains for primary CRMs

Almost all global consumption of CRMs is currently based on extraction from virgin mineral ores. CRMs from virgin ores are also called primary CRM. Value chains for primary CRMs include activities during exploration, extraction, beneficiation, refining and distribution. These value chains are complex and contain many stages that may create supply bottlenecks. A more secure supply of CRMs must therefore depend on diverse value chains having sufficient redundancy to compensate for unexpected halts or reduction in supply or process capacity in individual links. Additionally, it is important that the value chains are not disturbed in ways that hinder trade and distribution in a free market.

The value chains of CRMs are often complex and transnational where CRM-products may cross national borders several times during different steps of their processing before reaching end user quality. As a result, a single nation has limited capacity to regulate how these value chains operate.

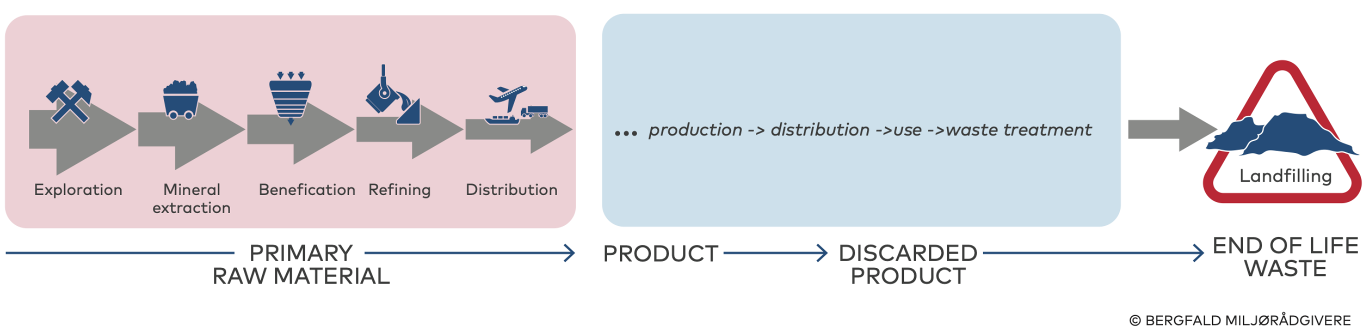


Figure 1.4 Simplified structure of the value chains for primary CRM-products with land filling as the most typical end of life treatment.
Illustration Bergfald Miljørådgivere.

Because primary CRM value chains are based on virgin mineral ores, a national strategy to strengthen these value chains often include measures that aim at ensuring necessary access to central mineral deposits and industrial capacity that can process the ore resources into refined end-user quality raw material products.

A challenge often associated with primary production of some CRMs is that they are only produced as a by-product together with a main product. This results in increased supply risk since reduced production of the main product will also result in a proportional reduction in production of the by-products. For the same reason, it is also difficult to increase the extraction of the by-products if demand increases more for these than for the main product. Examples of critical elements and raw materials that are only produced as by-products include helium, indium, gallium, germanium, rhenium, selenium and tellurium.

Another challenge to primary production of CRMs is a declining societal acceptance of mineral extraction in the local communities surrounding the area where minerals are available, which makes it increasingly difficult to expand primary production of many critical raw materials. Extraction of CRM-minerals are often associated with pollution, noise and dust dispersion, and the mining operation may seize areas and water resources that create conflicts with other interests.

CRM-production is not evenly distributed over the world. The global production of individual CRMs is often dominated by one or a few nations as shown in figure 1.5.

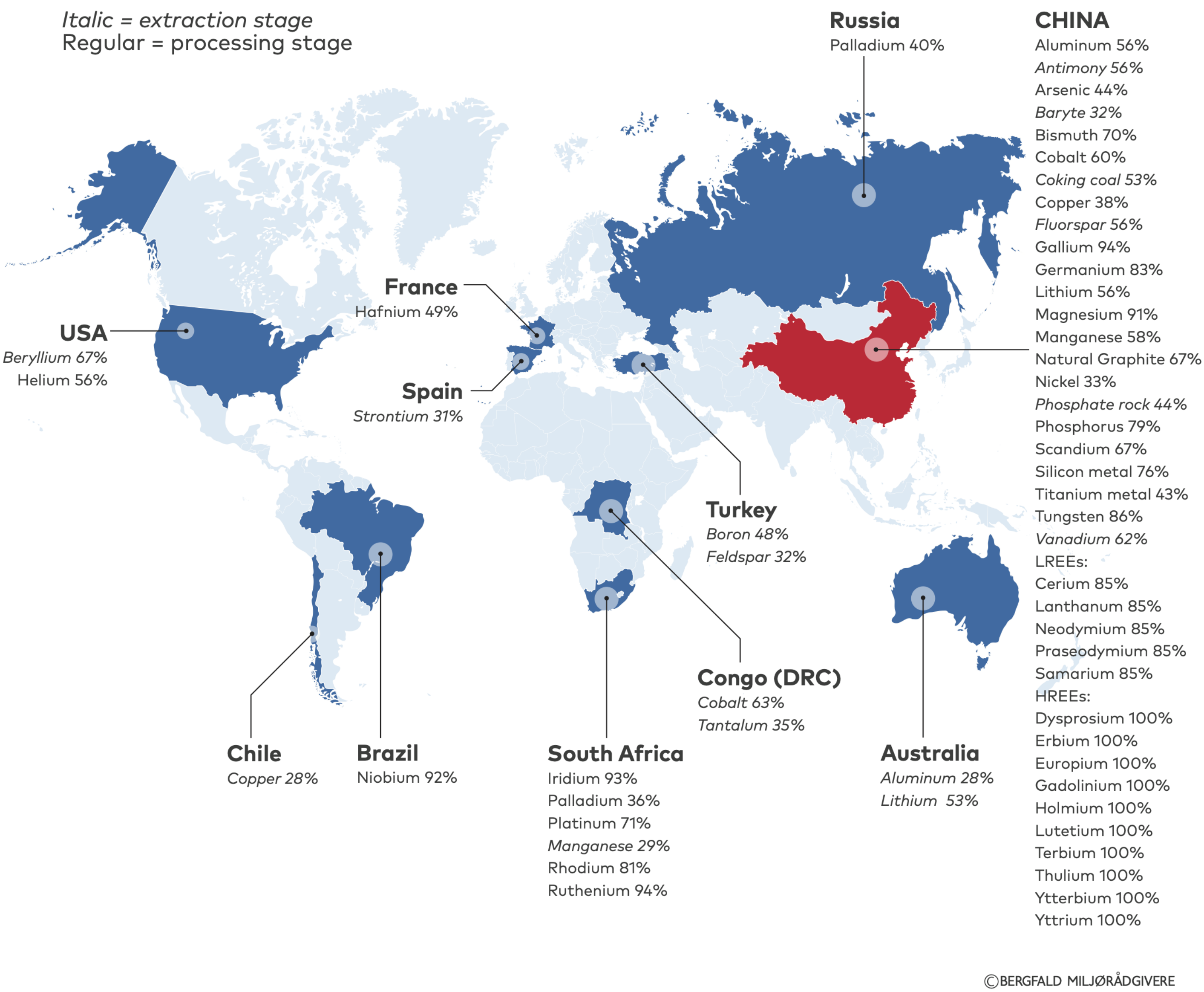


Figure 1.5 Main global suppliers of individual CRMs.
Source: European Commission, Study on the Critical Raw Materials for the EU 2023 – Final Report. Illustration Bergfald Miljørådgivere.

Figure 1.5 clearly shows China's dominant position as a supplier of critical raw materials and the corresponding low degree of self-sufficiency of Europe. Extraction and processing of many critical raw materials are concentrated in a small number of countries, where China has a unique position. This creates significant supply risks as a result of export restrictions that may be caused by changes in national framework conditions for CRM-producing industry or political instability in these countries. There are also examples of countries placing restrictions or bans on export of its own raw materials to strengthen the competitive situation for its own downstream industry. China has for example several times placed restrictions on its own CRM export, including rare earth elements which have created problems for European industry that are dependent on these metals.[8] It is also fair to point out that USA and some European countries have also historically had protectionist framework for domestic CRM production.

The market for some critical raw materials includes important niche uses that only require small volumes that are also often associated with highly fluctuating market prices. Due to small consumption volumes only a limited number of production facilities are necessary to cover these needs worldwide. This situation leads to higher vulnerability in the supply chain caused for instance by disruptive events like fires or accidents that may knock out a significant share of the global production resulting in temporary scarcity.

CRMs that experience large price fluctuations, will also result in reduced economic predictability for downstream industry which depend on these materials as input in their manufacturing operations. The market history of gallium may illustrate this situation. Gallium is used in LED lights and has therefore extensive applications in many areas of use, but only in small quantities per product resulting in a global marked for gallium of only ca 550 tons per year.[9] In addition, the gallium price has undergone major fluctuations in recent years and ranged between 200 and 800 USD per kg since 2015.

1.3.2 Value chains for secondary CRMs

Secondary value chains can provide the same raw materials as primary sources based on recycling from discarded products and sorted waste streams.[10] For this reason, there is a close link between strategies for critical raw materials and circular economy. A crucial step in a value chain for secondary critical raw materials is a well-functioning collection scheme that ensures that a high proportion of waste streams containing critical raw materials that can be recovered is made available for recycling. Because collected waste normally consists of mixtures of different

8. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_504
9. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-gallium.pdf
10. Although there may be some difference in the end product quality as recycled CRMs may contain other pollutants than the equivalent primary CRM.

materials, sorting systems are also required for separation of relevant material streams that are necessary for cost- and resource-efficient recycling. For example will WEEE, that contain high levels of many CRMs require extensive decomposition and sorting of individual components before cost efficient CRM-recycling is possible. As for primary CRM-value chains, secondary value chains can also be complex and entail collection and recycling operations in different countries.

What is Circular Economy?

Circular Economy was introduced as a political strategy in the European Union as part of a series of political initiatives that includes the Circular Economy Package from 2018 and the Circular Economy Action Plan that was launched in 2020 as a part of Green Deal. Central to the EU vision of a circular economy is the transition from linear to circular value chains where raw materials are recycled in closed technical loops that mirrors the closed loop of biological matter in the ecosphere.

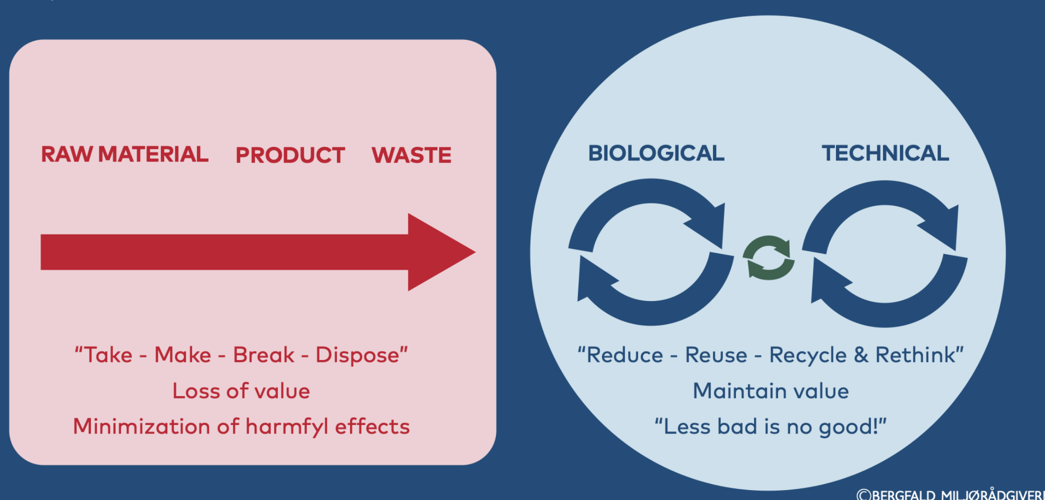


Figure 1.6 Comparison of linear and circular value chains.[11]
Illustration Bergfald Miljørådgivere.

Although the concept of circular economy is receiving increased attention, there are still many critical raw materials where the recycling rate is close to zero. For some CRMs this situation is a result of high recycling costs compared to the costs of primary production of the same products, for example for fluorspar and magnesium. But for other critical elements a mature and efficient recycling technology has yet to be developed, which is the reason no real recycling exists for

11. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

gallium that is used in all led lighting, lithium used in batteries and rare metals which are used in electronics, electric cars and wind turbines, take place. Even for basic metals where well-established recycling solutions exist, such as for copper (55% recycling rate), aluminium (32% recycling rate), magnesium (13% recycling rate) and nickel (16% recycling rate), we are very far away from a closed technical loop where raw materials can be said to flow to new generations of products without significant material loss.[12] Technological development may lead to more resource- and cost-effective recycling solutions that allow for recycling of more critical raw materials at higher recovery rates. However, this will require time and considerable R&D efforts. Figure 1.7 shows important stages in the product life cycle of secondary raw materials.

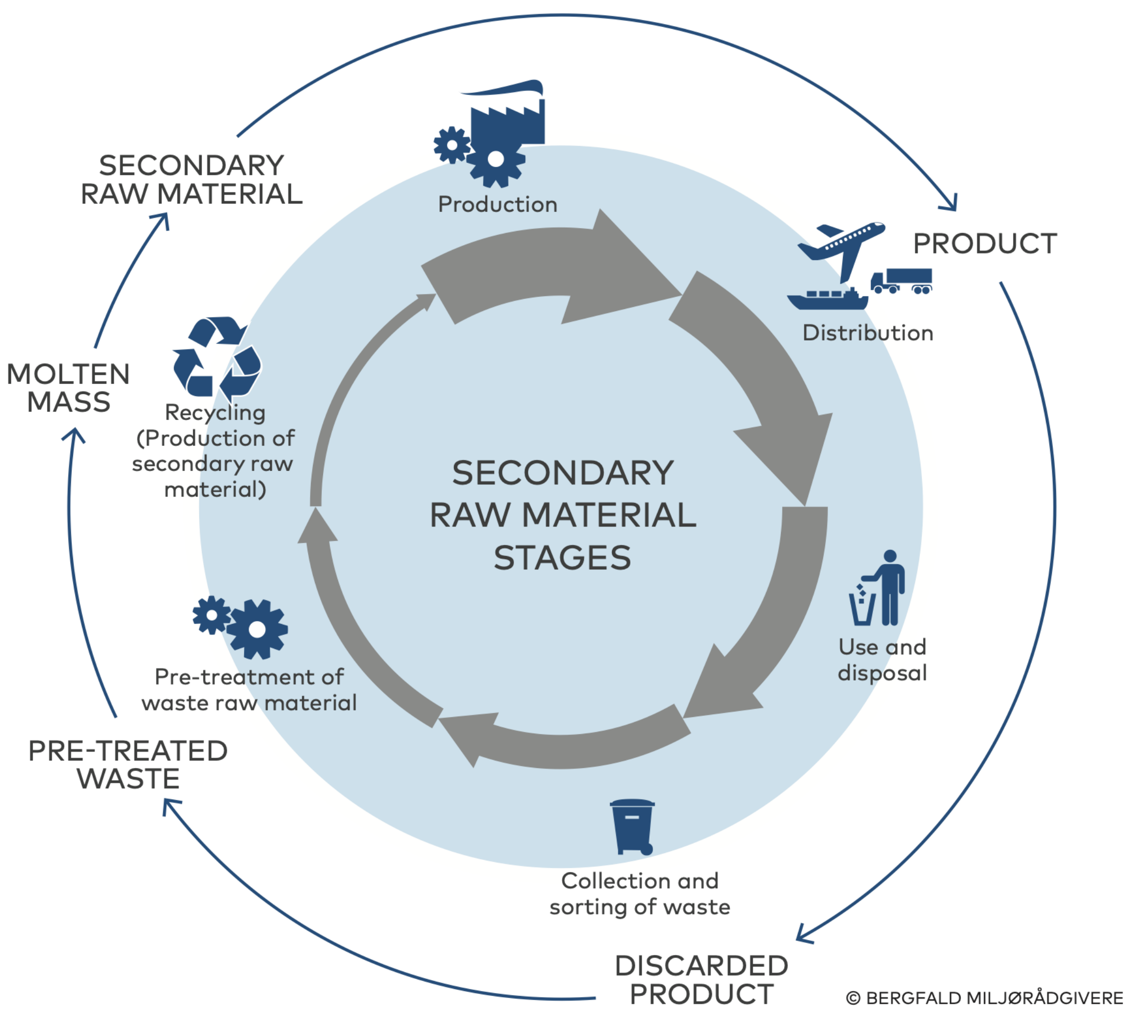


Figure 1.7 Simplified structure of the value chain for secondary CRM-products. Illustration Bergfald Miljørådgivere.

12. Study on the Critical Raw Materials for the EU 2023 Final Report, EU Commission

Figure 1.8 shows an integrated value chain for both primary and secondary raw materials. In a world with increasing overall consumption of raw materials and recycling rates less than 100%, some primary production will always be necessary.

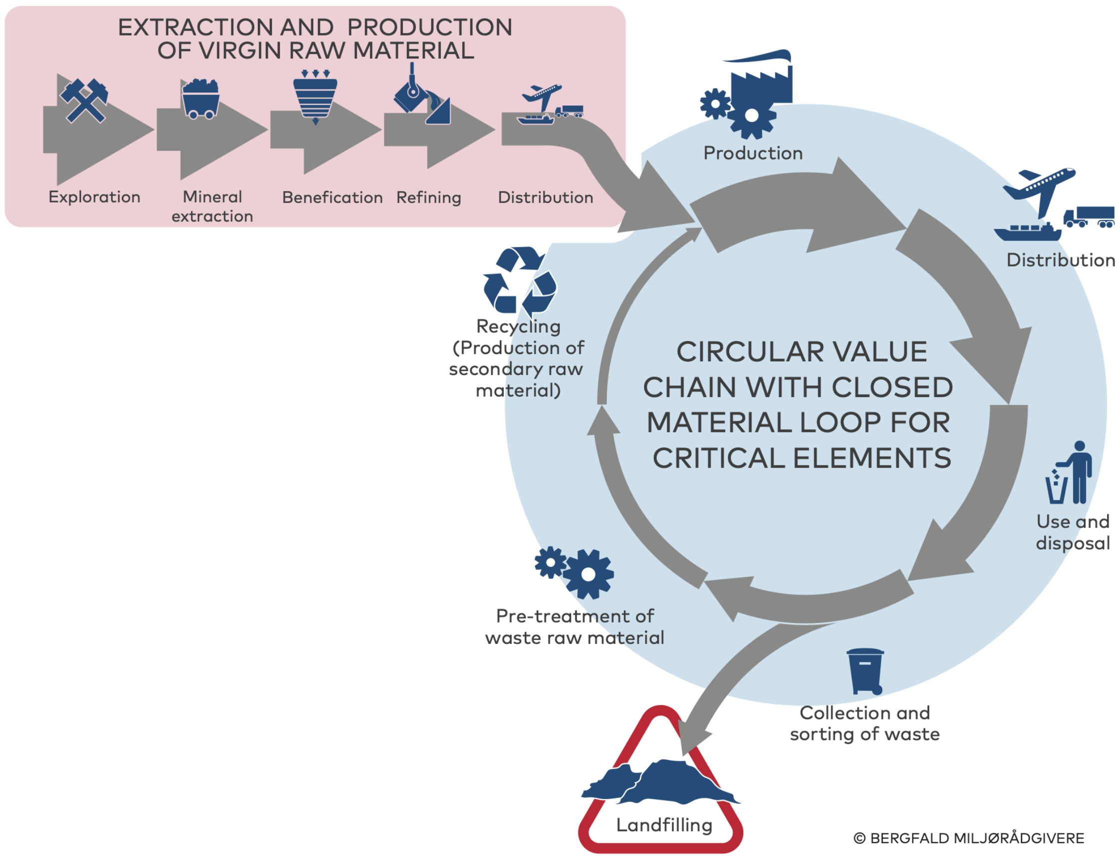


Figure 1.8 Integrated value chain for primary and secondary raw materials. Illustration Bergfald Miljørådgivere.

1.4 European strategy for critical raw materials

European concerns over increasing CRM-supply risks and corresponding vulnerability for affected industries and services caused EU to launch its *Raw Materials Initiative* in 2008.[13] This communication from the EU Commission have together with the *Action plan on critical raw materials* from 2020 provided a framework for initiatives to raise awareness and increase voluntary efforts to reduce European reliance on CRM-imports.[14] These non-regulatory instruments have however shown themselves to be insufficient tools for achieving necessary European CRM-supply security, and in March 2023 the EU-commission therefore

13. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0699:FIN:en:PDF
14. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1542

presented a proposal for a new regulation, The European Critical Raw Materials Act (CRMA), that aims to ensure the EU's access to a secure and sustainable supply of critical raw materials.[15] On November 13th 2023 it was announced that after negotiations the proposal had been approved by the European Parliament and Council.[16] Together with proposal for the Net-Zero Industry Act CRMA is also intended to increase the security of supply and robustness of EU's energy system, and to help reach the climate goals and accelerate circular economy as described in EUs Green Deal.

1.4.1 The European Union Critical Raw Materials Act (CRMA)

The European Union Critical Raw Materials Act (CRMA) contains 47 articles collected in ten chapters. Chapter 1 provides general provisions through Article 1 on subject matter and objectives which declares that the purpose of the CRMA is to "ensure the Union's access to a secure and sustainable supply of critical raw materials." This will be achieved through strengthening the different stages of the strategic raw materials value chain and shall be achieved through set targets for increased Union capacity to extract the ores, minerals or concentrates and further Union processing capacity for end user quality raw materials, and Union recycling capacity for CRM from waste.

Chapter 2 describes the framework for defining and updating EUs lists of critical and strategic raw materials. EU introduced its first list of critical raw materials in 2011 and have updated this list every three years since. The raw materials that are listed as critical or strategic are shown in the following tables and given a short description in the appendixes.

Table 1.1 Raw materials listed as critical in CRMA

Critical raw materials	
Antimony	Light Rare Earth Elements (Gadolinium)
Arsenic	Light Rare Earth Elements (Lanthanum)
Bauxite/Alumina/Aluminium	Light Rare Earth Elements (Neodymium)
Baryte	Light Rare Earth Elements (Praesodymium)

15. https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en
16. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_5733

Beryllium	Light Rare Earth Elements (Promethium)
Bismuth	Light Rare Earth Elements (Samarium)
Boron	Lithium
Cobalt	Magnesium
Coking coal	Manganese
Copper	Nickel - battery grade
Feldspar	Niobium
Fluorspar	Phosphate rock
Gallium	Phosphorous
Germanium	Platinum Group Metals (Iridium)
Graphite	Platinum Group Metals (Palladium)
Hafnium	Platinum Group Metals (Palladium)
Helium	Platinum Group Metals (Platinum)
Heavy Rare Earth Elements (Dysprosium)	Platinum Group Metals (Rhodium)
Heavy Rare Earth Elements (Erbium)	Platinum Group Metals (Ruthenium)
Heavy Rare Earth Elements (Holmium)	Scandium
Heavy Rare Earth Elements (Lutetium)	Silicon metall
Heavy Rare Earth Elements (Terbium)	Strontium
Heavy Rare Earth Elements (Thulium)	Tantalum
Heavy Rare Earth Elements (Ytterbium)	Titanium metal
Heavy Rare Earth Elements (Yttrium)	Tungsten
Light Rare Earth Elements (Cerium)	Vanadium

Table 1.2 Raw materials listed as strategic in CRMA

Strategic raw materials	
Bauxite/Alumina/Aluminium	PGM (Palladium)
Bismuth	PGM (Palladium)
Boron	PGM (Platinum)
Cobolt	PGM (Rhodium)
Copper	PGM (Ruthenium)
Gallium	Rare Earth elements for magnets (Dysprosium)
Germanium	Rare Earth elements for magnets (Cerium)
Graphite - battery grade	Rare Earth elements for magnets (Gadolinium)
Lithium	Rare Earth elements for magnets (Neodymium)
Magnesium	Rare Earth elements for magnets (Praesodynium)
Manganese	Rare Earth elements for magnets (Samarium)
Nickel	Rare Earth elements for magnets (Terbium)
PGM (Iridium)	Silicon metall

Chapter 5 contains requirements regarding sustainability. Section 1 contains articles that provides provisions for developing circular markets for critical raw materials. Article 25 describes national measures for circularity and requires that all states bound by the regulation develop a program which includes measures designed to increase resource efficiency when consuming CRMs and to expand the reuse of CRM-containing products and components. This program may be integrated into a national waste management plan, and shall facilitate increased collection, sorting and processing of waste with high critical raw materials recovery potential and ensure their introduction into the appropriate recycling system. To support this development, national research and innovation programs shall include measures to increase the technological maturity of recycling technologies for CRMs, promote circular design and material efficiency and substitution alternatives for CRMs.

Article 25 also includes provisions on upskilling and reskilling of workforce in the CRM-value chain, application of the producer pays principle and extended producer responsibility, CRM-exports and EU-quality standards. Special attention is given to WEEE where CRM-containing components and CRM recovery rates must be quantified and reported on a format that will be provided by the EU Commission. The Commission will also provide additional provisions that describe which products, components and waste streams should at a minimum be considered as having a potential for recovering CRMs.

Article 26 requires certain mining operators to perform a preliminary economic assessment study regarding the potential recovery of critical raw materials from extractive waste. This study must at a minimum contain an estimation of the quantities and concentrations of critical raw materials contained in the extractive waste and in the extracted volume and an assessment of their technical and economic recoverability.

States bound by CRMA are required to establish a database of closed and abandoned extractive waste facilities located on their territory where the characteristics of the waste sites or geological conditions do not make the presence of potentially technically recoverable quantities of critical raw materials unlikely. This database shall contain information on the location, areal extent and waste volume and approximate quantities and concentrations of all raw materials contained in the extractive waste. The same states must also adopt and implement measures to promote the recovery of critical raw materials from extractive waste. Where available information could indicate the presence of potentially economically recoverable quantities of critical raw materials, the states must conduct representative geochemical sampling or a more detailed sampling with subsequent chemical and mineralogical characterisation involving core logging or equivalent techniques.

Article 27 and 28 gives provisions on the labelling of certain products that may contain permanent magnets and reporting scheme for the share of individual CRMs these magnets contain.

Article 29 and 30 in Section 2 describes requirements for declaration and certification of Environmental footprint, including rules for national certification schemes seeking recognition by the EU Commission. Section 3 contains regulations regarding free movement (Article 31) and conformity and market surveillance (Article 32) related to products incorporating permanent magnets and CRMs for which the environmental footprint must be declared.

1.5 Implications of CRMA for the Nordic countries

If the proposed CRM Act is accepted, it will have a profound impact and effects on many sectors both private and public, in the Nordics as well as for the rest of EU. The mineral sector together with the metallurgic, waste and recycling industries will all experience significant changes in their framework conditions as provisions to strengthen CRM value chains take effect. National polices will have to be updated and include a plan for how specific CRM-recycling targets shall be met, programs for strengthening relevant value chains and systems must be designed and set up, and a scheme for monitoring progress towards set goals must be implemented that include updated national statistics that include material streams of individual CRMs during different stages of their product life.

CRMA requires the Nordic countries bound by CRMA to prepare national polices on how to contribute to the EU CRMA goals for 2030 which includes:

- That the EU extracts at least 10% of the critical raw materials needed for its production.
- That the EU processes at least 40% of the critical raw materials needed for its production.
- That recycling covers at least 25% of the EU's need for critical raw materials needed for its production.
- That the EU does not cover more than 65% of its need for the various critical raw materials through imports from individual countries.

As part of this process national programs for exploration of CRM-mineral resources, updates in governmental operational permit practice and national statistics that cover extraction, processing and consumption of CRMs must be established.

1.5.1 Nordic regions expected to implement CRMA

Denmark, Sweden and Finland together with Åland are as member states in EU required to implement CRMA into national legislation. Although Norway and Iceland are not members of the EU, the CRMA is still expected to take national effect as a part of the EEC-agreement. The Faroe Islands are a self-governing nation within the Kingdom of Denmark. They are not part of the European Union or part of the EEC-agreement and is therefore not expected to have to follow CRMA.[17] Greenland was a member of EU until 1985. Since then, Greenland has a special fisheries agreement and has been accepted as one of the overseas countries and territories with special association with the EU.[18] It is unclear whether CRMA will take effect in Greenland.

17. http://brexitlegalguide.co.uk/faroe-islands/
18. https://www.norden.org/en/information/facts-about-greenland

1.5.2 Special Nordic conditions

Compared to other EU-member states with larger populations, the Nordic countries generate smaller amounts of waste materials. Low population density in northern regions of Finland, Sweden and Norway also leads to relatively small volumes of materials and waste being transported over long distances.

Nordic countries have well developed infrastructure for collection and sorting of basic waste streams that can form a foundation for collection of additional waste streams with CRM-recycling potential. Regardless of rational integration of new collection schemes into existing systems, collection and sorting of new waste streams will always entail additional costs and further development of waste infrastructure. There are also several metallurgical plants and recycling facilities that may facilitate increased CRM- recycling. Sweden and Finland have a well-developed mineral sector with both advanced technology and expertise in processing of mineral products. A more detailed description of Nordic waste collection systems is provided in Appendix 4 of this report.

Increased Nordic recycling of CRMs can provide benefits beyond the profitability of individual companies involved in new or expanded value chains for secondary CRM-production, and includes increased circularity, reduced landfilling, stable and sustainable workplaces and secure access to raw materials for the downstream processing industries.

2. Applications of critical raw materials (CRM)

CRMs have countless applications in modern products and materials. This chapter presents an overview of central CRM-applications as a foundation for a further discussion on which waste streams that may serve as a feedstock for CRM-recycling. Table 2.1 provides an overview of significant applications of critical and strategic raw materials as defined by EU per December 2023. A more detailed description of each CRM can be found in the Appendices.

Table 2.1 Overview of significant applications of EU CRMs and SRMs.

CRM/SRM	Applications
Antimony	Flame retardent, ammunition, alloys, batteries, solder
Arsenic	LED light, glass, lead alloy, wood preservation
Baryte	Drilling fluid, filler in paint, plastic, contrast fluid
Bauxite/Aluminium	Cans and packaging, Light weight construction material, vehicles, EE-products, household products
Beryllium	EE-products, alloys
Bismuth	Lead free ammunition and solder, EE-products, ceramics, pharmaceuticals, rocket propellant
Boron	Light weight materials, fertilizer, magnets, heat resistant glass, eye wash, detergent
Cobalt	Alloys, catalyst, batteries, magnets, pigment
Coking coal	Reducing agent, additive in steel production, carbon fibres
Copper	Pipes, EE-products and electric infrastructure, construction material, bioside, pigment
Feldspar	Glass and ceramics, filler in paint, plastics, rubber and paint

Fluorspar/Fluorine	Industrial chemicals, organic chemicals and materials including teflon and Gore Tex, pharmaceuticals, batteries,
Gallium	LED-light, magnets, screens, infra red detector
Germanium	Infra red optics, polymerisation catalysts, reflector in projector, transistor/diodes, satelite solar cells, optical fibers
Graphite	Alloys, batteries, electrode and refractory material in metal production, lubricant
Hafnium	Nuclear control rods, jet engines, refractory ceramics, alloys, tools
Helium	Welding/blanket gas, cryogenics, MRI, athmosphere for deep diving, balloons
HREE (Dysprosium)	Magnets, laser, ceramics, alloys, pigments
HREE (Erbium)	Magnets, glass, ceramics, EE-products, fiber optics, laser, alloys, catalysts
HREE (Holmium)	Magnets, glass, alloys, laser
HREE (Lutetium)	Magnets, phosphors, scintillators, catalysts, laser
HREE (Terbium)	Magnets, glass, alloys, laser, X-ray
HREE (Thulium)	Ceramics, laser, X-ray, magnets, EE-products
HREE (Ytterbium)	Magnets, transistors/diodes, alloys, ceramics, laser, optics, SOFC
HREE (Yttrium)	Catalysts, phosphors, magnets, ceramics, glass, pigments, EE-products, alloys, pigment, screens, lenses, laser/radar
Lithium	Batteries, ceramics, lubricants, pharmaceuticals, alloys (steel and aluminium)
LREE (Cerium)	Alloy, catalyst, pigment, glass, SOFC, super conductor, optical products, arc lamp, polishing powder, lighter flint
LREE (Europium)	Alloys, pigments, laser, X-ray

LREE (Gadolinium)	Magnets, EE-products, medical products, ceramics, alloys, superconductors, laser
LREE (Lanthanum)	Catalysts, pigment, glas, ceramics, lenses, batteries, SOFC
LREE (Neodymium)	Magnets, glass and ceramics, catalysts, pigment, alloys, lasers
LREE (Praesodymium)	Magnets, glass and ceramics, pigments, SOFC, alloys,
LREE (Promethium)	Synthetic nuclear isotope
LREE (Samarium)	Magnets, glass, alloys
Magnesium	Light weight construction material, tools, bicycles and wheel chairs, desulphurization agent in steelmaking, EE-products
Magnetic REE (Dysprosium)	Magnets, laser, ceramics, alloys, pigments
Magnetic REE (Erbium)	Magnets, glass, ceramics, EE-products, fiber optics, laser, alloys, catalysts
Magnetic REE (Europium)	Magnets, alloys, pigments, laser, X-ray
Magnetic REE (Gadolinium)	Magnets, EE-products, medical products, ceramics, alloys, superconductors, laser
Magnetic REE (Holmium)	Magnets, glass, alloys, laser
Magnetic REE (Lutetium)	Magnets, phosphors, scintillators, catalysts, laser
Magnetic REE (Neodymium)	Magnets, glass and ceramics, catalysts, pigment, alloys, lasers
Magnetic REE (Praesodynium)	Magnets, glass and ceramics, pigments, SOFC, alloys,
Magnetic REE (Samarium)	Magnets, glass, alloys
Magnetic REE (Terbium)	Magnets, glass, alloys, Laser, x-ray
Magnetic REE (Thulium)	Magnets, EE-products, ceramics, laser, X-ray, magnets

Magnetic REE (Ytterbium)	Magnets, transistors/diodes, alloys, ceramics, laser, optics, SOFC
Manganese	Alloys, fertilizer, batteries
Nickel	Alloys, coating, batteries, catalyst
Niobium	Alloys (high strength temperature resisitant), EE-products (capacitors, magnets etc)
PGM (Iridium)	Catalysts, industrial scoops
PGM (Palladium)	Catalysts, EE-products, dental crowns, jewlery
PGM (Platinum)	Catalysts, dental crowns, jewlery, medical equipment
PGM (Rhodium)	Jewlery, catalysts
PGM (Ruthenium)	EE-products, jewlery, catalysts
Phosphate	Synthetic fertilizer, nutrient additive, flame retardent, food
Phosphorous	Fireworks, lubricant additive, chemical and defence applications
Scandium	EE-products, Solid Oxide Fuel Cells, light weight alloys
Silicon, metall	Photovolaics, semiconductors/microchips, alloys
Strontium	Pyrotechnics, ceramic magnets, magnets, luminating paint
Tantalum	Medical and laboratory equipment, alloys, coocking elements, EE-products (capacitors)
Titanium, metal	Medical implants, EE-products, light weight alloys, military and aeronatics and space applications
Tungsten	Cutting and drilling bits, mobile phones, alloys, welding rods, projectiles
Vanadium	Batteries, catalysts, alloys

As can be seen from Table 2.1 dominating applications of CRMs and SRMs include use as chemical components in alloys and magnets. Another important use of many CRMs is as catalysts that support chemical reactions and cleaning of flue gases. CRMs have also many applications in glass and ceramics often as a pigment.

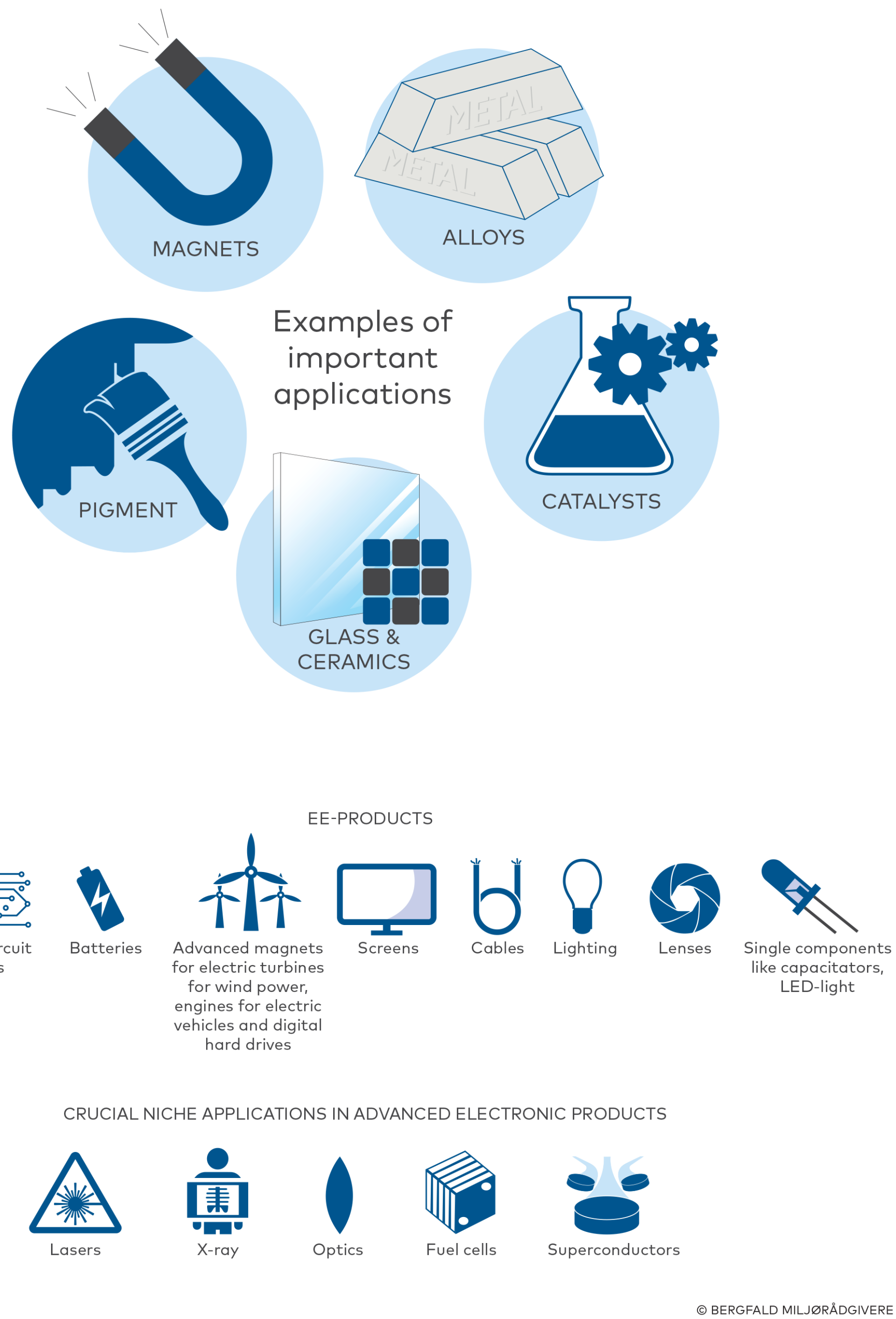


Figure 2.1 Important applications of CRMs.
Illustration Bergfald Miljørådgivere.

CRMs are essential inputs in almost all electric and electronic products and components from printed circuit boards to batteries. CRMs also form the main components of advanced magnets necessary for making electric turbines for wind power, engines for electric vehicles and digital hard drives. Many CRMs have crucial niche applications in advanced electronic products like lasers, x-ray, optics, fuel cells, superconductors. Some CRMs have important applications for defence (projectiles, radar and electronics), nuclear power production (control rods and cooling) and space programs (rocket propellant, electric power production, thermic insulation).

Large amounts of CRMs are also found in metallic construction materials either as the main material component (aluminium, magnesium or copper) or minor components in alloys. Paint and other coating often contain pigments made from CRMs (titanium, copper, cobalt mm).

All food products, both animalistic and vegetarian contain recyclable phosphate. Other important applications of CRMs include additives in drilling fluids (barite), medical products (titanium, boron, lithium, gadolinium) and ammunition (copper, antimony, bismuth)

Many CRMs are found in countless household products like EE-products, tools, sports equipment, furniture, decorating articles packaging and textiles.

CRMs are also found in many household appliances as flame retardants in textiles, furniture and plastic materials (antimony, and phosphorous), and as coating of cooking equipment (fluorine) and tools and equipment (tungsten and nickel).

3. Waste types with CRM recycling potential

Recycling of CRMs require available waste materials that may serve as feedstock for the recycling process. Waste materials are generated and can be collected at many stages in a product life. During extraction of minerals which is the first step in production of most raw materials, tailings are formed when relevant minerals are separated from residual materials that have no further use. Depending on the efficiency of the separation process, varying levels of minerals of economic value will follow the tailings from which it may be extracted in a later process. During later refining processes where the raw material extracted from the ore is upgraded for different types of use, additional waste streams are created that may contain recoverable levels of CRMs. In later stages, components containing CRM are assembled or mixed into a final product that may then be used separately or as part of larger integrated system. Each step on this pathway may serve as a collection point for waste streams that may be used as feedstock for CRM-recycling. This situation is illustrated in figure 3.1.

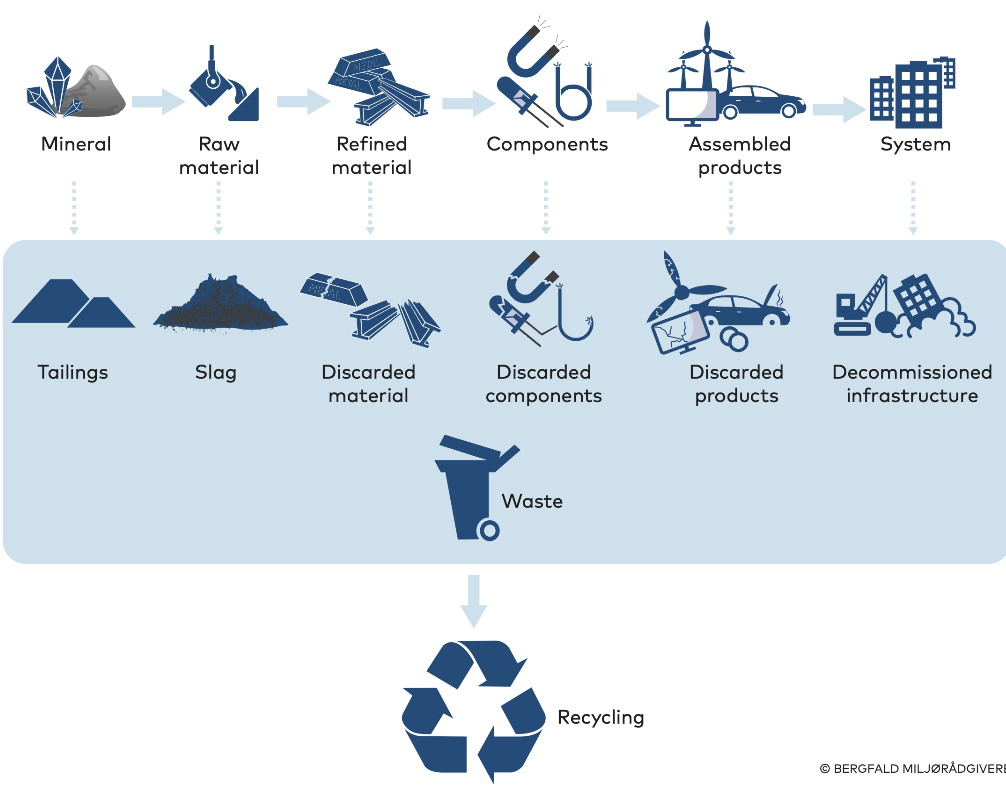


Figure 3.1 Stages in a product life from which waste streams for CRM-recycling may be collected.
Illustration Bergfald Miljørådgivere.

3.1 Waste streams containing CRMs

Based on the description in chapter 2, waste streams that can be expected to contain CRMs may be identified. In EU waste statistics are collected on a national level for around 30 waste categories. Table 3.1 summarizes waste streams that can be expected to contain significant amounts of recyclable CRMs, and details relevant components of these waste streams. A detailed description of Nordic waste streams can be found in the Appendices.

Table 3.1 EU waste categories with national statistics for EU [19]

EU waste category	Waste code includes	Waste streams with CRM
Industrial waste		
Acid, alkaline or saline wastes	Spent inorganic acids and salts from industial processes that includes bleach and fixer solutions, etching solutions, developer solution, water based degreasing liquids, lime mud, flux and saline wastes from hydrometallurgical processes and hot galvanising	Spent phosphorous- and fluoridic acid, CRM-oxides and -halogenides, CRM-containing sludge and wastewater from metalurgical processes
Chemical wastes	Catalysts, medicines, paint, dyestuff, pigments, varnish, inks and adhesives, sludges, unused explosives and waste ammunition, used chemicals and pressurised gases, tars and bitumen, carbon anodes, fuels and emulsions, dust and slag from metallurgic industry, sludge and filter cakes	Spent catalysts, pigments, waste ammunition, spent metal coatings, discarded teflon coatings and gore tex fibres, syntetic fertilizer residues, wood preservation (arsenic), dust and slag from metallurgic industry (Al, Cu, Mn, Ni), sludge and filter cakes

19. Guidance on classification of waste according to EWC-Stat categories Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics Version 2, Eurostat

Industrial effluent sludges	Sludges and solid residues from industrial wastewater treatment and industrial cleaning processes, wastes from soil and groundwater remediation, drilling mud	Sludge from CRM-polluted waste water treatment, waste from metal coatings, discarded drilling fluids (baryte)
Combustion wastes	Wastes from flue gas cleaning, sludges, filter dust and cakes, fly ashes, slags, drosses, skimmings from copper and aluminium and steel industry, boiler dusts and ashes from thermal processes	CRM enriched waste from flue gas cleaning, sludges, filter dust and cakes, fly ashes, slags, drosses, skimmings from copper and aluminium and steel industry, boiler dusts and ashes from thermal processes
Spent solvents	Organic compounds, halogenated hydrocarbons, organic washing liquids, mother liquors, fluorinated refrigerants from chemical industries including extraction and cleaning processes, mechanical engineering and surface treatment	Fluorinated solvents, pharmaceutical solvents, solvents from metalurgical processes and metal coating
Used oils	Engine, gear, hydraulic and lubricating oils, oils for insulation and heat transmission, emulsions from metal surface shaping and residues from tank cleaning	Spent lubricating oils containing CRM additives (graphite, litium, phosphorus, fluorinated hydrocarbons)
Biological waste		
Animal and mixed food waste	Animal waste food incl. Sludges (phosphate)	Animal waste food incl. Sludges (phosphate)
Animal faeces, urine and manure	Slurry and manure including spoiled straw (phosphate)	Slurry and manure including spoiled straw (phosphate)
Vegetal wastes	Vegetal food waste including sludges from washing and cleaning	Vegetal food waste including sludges from washing and cleaning
Common sludges	Waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing (Phosphate)	Waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing (Phosphate)
Health care and biological wastes	Bodyparts and organs, contaminated plastic and textiles, diapers, sharps, spent supplies and residual matter	Fluorinated plastics, diagnostic fluids (Gd), dicarded metal body implantates (Ti)

Metallic waste		
Metal wastes, ferrous	Scrap metal and alloys, end-of-life-vehicles (iron and steel alloys), metal dust and shavings, metallic construction and demolition waste, shredding residue, bottom ash metal	Scrap metal and alloys, end-of-life-vehicles (iron and steel alloys), construction and demolition waste, shredding residue, bottom ash metal
Metal wastes, mixed ferrous and non-ferrous	Scrap metal and alloys, end-of-life-vehicles, construction and demolition waste, shredding residue, bottom ash metal, metal dust and shavings, metal packaging	Scrap metal and alloys, end-of-life-vehicles (copper, aluminium and other CRM-alloys), construction and demolition waste, shredding residue, bottom ash metal, metal packaging.
Metal wastes, non-ferrous	No ferrous scrap metal like aluminium, copper, zinc, lead, tin and alloys. Cables, galvanized metal, end of life vehicles, construction and demolition waste, shredding residues.	Metallic packaging, mixed scrap metal and alloys, construction and demolition waste (Al, Cu and CRM-alloys)
Non-metallic sorted materials		
Glass wastes	Waste glass packaging, glass waste from production of glass and glass products, and from sorting and recycling processes, glass powder	CRM-containing glass
Plastic wastes	End-of-life-plastic from vehicles, WEE, packaging and other products	End-of-life-plastic from vehicles, WEE and other products containing CRM-based flame retardants, filler or pigments
Rubber wastes	End-of-life-tyres	CRM containing rubber components and metal fiber
Textile wastes	Textile and leather waste, waste from fiber preparation and textile manufacturing, footwear	Discarded textiles containing flame retardants (antimon and phosporous), pigments and goretex -textiles
Wood wastes	Wooden packaging, saw dust, shavings and cuttings, waste bark, wooden construction materials	Wood waste containing historic wood preservation (arsenic and copper)

WEEE and vehicles		
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	WEEE, household equipment, IT-equipment, electric tools, electric components removed from end of life vehicles	WEEE, household equipment
Discarded vehicles	End-of-life-vehicles	Alloys and other CRM-containing materials from end-of-life-vehicles
Batteries and accumulators wastes	All kinds of batteries and accumulators (Manganese, aluminium, nickel, cadmium, mercury, lead, litium and graphite)	Batteries and accumulators containing manganese, aluminium, nickel, litium and graphite.
Mixed waste		
Household and similar wastes	Mixed municipal waste, kitchen waste, household equipment, undifferentiated goods	CRM containing household waste
Mixed and undifferentiated materials	Mixed and composite packaging, Welding waste, metal waste contaminated with dangerous substances	CRM-containing mixed waste
Mineral waste		
Mineral waste from construction and demolition	Concrete, bricks, and gypsum waste, tiles and ceramics, insulation materials	CRM containing bricks, and gypsum waste, tiles and ceramics
Other mineral wastes (W122+W123+W125)	Mineral wastes from mining and quarrying, blasting material (P?) and grinding bodies (Tungsten), casting cores and moulds, linings and refractories from all thermal processes. Waste from production of cement, ceramics and glass	CRM-enriched tailings form mining operations, linings and refractories from all thermal processes. CRM-enriched waste from production of cement, ceramics and glass

Waste from waste treatment		
Mineral wastes from waste treatment and stabilised wastes	Bottom ash, slag, fly ash and waste from flue gas treatment from waste incineration	Bottom ash, slag, fly ash and waste from flue gas treatment from waste incineration
Sludges and liquid wastes from waste treatment	Bio-residue from biogass production	Bio-residue from biogass production
Sorting residues	Sorting residues from mechanical sorting processes for waste, like screening, fluff-light fraction, non composted fraction of biodegradable waste	CRM enriched sorting residues from mechanical sorting processes for waste
Soils	Soil incl excavated soil from contaminated sites	Arsenic contaminatied soil

Industrial waste

Industrial waste includes acids, alkaline or saline wastes, other chemical waste, sludges, solvents and oils, slags, scales, dusts, spent process equipment etc. Acids may be phosphorus acid or hydrofluoric acid or contain dissolved CRM-metals or phosphate or fluoride. Alkaline or saline waste may contain CRM-oxides or halogenides.

Other chemical wastes include spent catalysts, pigments, spent metal coatings, synthetic fertilizer residues, wood preservation, dust and slag from metallurgic industry, sludge and filter cakes, waste silicones and waste from ammunition and explosives.

Spent catalysts may contain PGM-metals, graphite, nickel metal, CRM-metal oxides like cobalt, germanium, REE and vanadium.

Pigments may contain salts of titanium, cobalt and copper. Spent metal coatings may contain nickel, copper or fluor (Teflon). Synthetic fertilizer residues may contain phosphate and older spent wood preservation may contain arsenic and copper.

Dust and slag from metallurgic industry are a waste stream of special interest because it often consists of large volumes of homogenous (or at least predictable) chemical composition that are relatively easy to separate and collect. Compared to other waste streams metallurgic dust and slag often contain high levels of aluminium, cobalt, copper, fluorine, gallium, rare earth elements, manganese, magnesium, nickel and phosphorus. Sludge and filter cakes from industrial processes may also contain recoverable levels of many CRMs depending on which process they come from.

Selected waste streams from aluminium production may contain increased levels of fluor and gallium, while selected waste streams from steel production may contain increased levels of manganese, vanadium, nickel and copper. Waste from electric-arc furnace processes (EAF) in copper, nickel and zinc production are also often enriched with CRMs. The same goes for spent industrial extraction fluids.

Waste ammunition may contain copper, antimony and bismuth.

Biological waste

All biological waste contain phosphate that can be recycled. Important biological waste streams are animal and vegetal food waste and waste from growing and processing food products, including animal faeces, urine and manure. Sludge also often contains high levels of organic matter with recoverable phosphate. Some biological waste, especially from the health care sector may represent infection risks that limit recycling options.

Metallic waste

Metallic waste is often collected in sorted fractions due to their high value and cost-effective recycling options. The dominating metal waste fraction is ferrous metal that include steel and iron scrap. The most important non-ferrous metals include aluminium, magnesium and copper. Important sources of metal waste are household and industrial waste, deconstruction and demolition projects and scrapped vehicles. Metallic scrap contains CRMs both as the main chemical component (aluminium, magnesium, copper and titanium) and as minor alloy components (antimony, beryllium, tin, bismuth, copper, gallium, germanium, hafnium, rare earth elements, lithium, manganese, nickel, scandium, tantalum, tungsten and vanadium).

Non-metallic sorted materials

Some non-metallic materials are also often collected as sorted waste streams and include glass, plastic, rubber, textile and wood waste. Few of these waste streams are expected to contain materials with recoverable levels of CRMs. Most glass are made of silicon oxide and may also contain CRM-based pigments and other additives. Plastic may contain CRM-based pigments, fillers or flame retardants. The dominant fraction of rubber waste is discarded tyres made with neodymium catalysts and often contain CRM-additives and alloyed steel fibres. Some textiles are made from fluor based materials (Gore tex) or may contain CRM-based flame retardants (phosphorous or antimony).

WEEE and vehicles

One of the most important waste streams for recycling of CRMs is electric and electronic equipment waste (WEEE). WEEE include both household applications and industrial equipment. CRMs can be found in components like magnets, batteries and printed circuit boards, and as additive in alloys, glass and ceramics.

Discarded vehicles are another waste stream with high potential for CRM-recycling and contain many WEEE-components in addition to valuable alloys used as construction materials. Electric vehicles contain more CRMs in the battery and engine compared to fossil fuel-based cars. Fossil fuel-based cars often contain PGM as catalysts in the exhaust system.

Mixed waste

Mixed waste arises from both households and industry and is often consisting of a myriad of waste materials that is difficult to separate. Extraction of CRMs from the ash after incineration may therefore be an alternative recycling strategy if pre-incineration sorting is not possible.

Mineral waste

Mineral waste includes inorganic waste from both mining operations and from construction and demolition projects. One important mineral waste stream that contain huge amounts of CRM, albeit often in low concentrations is tailings from processing of mineral ores. Mineral waste from construction and demolition projects includes concrete, gypsum and ceramic materials.

Waste from waste treatment

Waste treatment generates several distinct waste streams that include combustion waste, mineral wastes from waste treatment and stabilised wastes, sludges and liquid wastes from waste treatment and residues from sorting processes. Combustion waste include bottom ash and fly ash from waste incineration that are generated in large volumes that can easily be collected for further treatment, and contain all CRMs, albeit normally in low concentrations.

3.1.1 Nordic waste streams

Table 3.2 shows reported amounts of Nordic waste. Waste data for years after 2020 was not available at the time of writing of this report. Because the waste statistic for 2020 is affected by abnormal activity levels and living conditions during the Covid epidemy, similar waste data is also provided for 2018 and 2016. Similar overview of waste streams for each Nordic country is provided in Appendix 2.

Table 3.2 Nordic waste streams, Source: Eurostat

Nordic waste streams

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	707.206	714.959	801.640
Chemical wastes	1.467.837	1.392.970	1.694.405
Industrial effluent sludges	563.867	616.813	620.702
Combustion wastes	4.877.443	4.598.078	3.863.324
Spent solvents	93.786	105.702	132.313
Used oils	307.681	276.431	366.816
Biological waste			
Animal and mixed food waste	1.996.928	2.342.130	2.345.674
Animal faeces, urine and manure	863.862	1.198.259	1.286.565
Vegetal wastes	2.362.257	2.396.042	2.614.528
Common sludges	1.317.030	1.457.889	1.356.990
Health care and biological wastes	15.617	15.828	16.909
Metallic waste			
Metal wastes, ferrous	2.896.222	3.875.930	2.904.817
Metal wastes, mixed ferrous and non-ferrous	2.278.049	2.108.505	1.725.505
Metal wastes, non-ferrous	518.098	710.612	799.373

Non-metallic sorted materials			
Glass wastes	689.800	767.912	747.076
Plastic wastes	770.114	908.112	877.271
Rubber wastes	208.109	222.176	195.367
Textile wastes	44.778	58.187	38.672
Wood wastes	8.092.148	7.823.389	6.594.906
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	631.546	529.910	631.041
Discarded vehicles	947.862	1.025.075	967.165
Batteries and accumulators wastes	99.980	70.946	94.727
Mixed waste			
Household and similar wastes	7.259.130	7.442.637	7.487.945
Mixed and undifferentiated materials	4.149.760	3.735.809	3.184.800
Mineral waste			
Mineral waste from construction and demolition	10.597.259	11.290.808	11.639.791
Other mineral wastes (W122+W123+W125)	201.823.989	196.187.278	206.161.659

Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	3.139.678	3.447.011	3.349.061
Sludges and liquid wastes from waste treatment	175.318	274.399	335.157
Sorting residues	4.501.799	4.429.086	3.599.040
Soils	29.661.398	40.261.187	31.439.538
Total	**293.058.551**	**300.284.070**	**297.872.777**

As can be seen from table 3.2, around three million tonnes of Nordic waste that may contain CRMs is generated each year. Only a small part of this waste consists of materials with recoverable amounts of CRMs, and it will be an important task for future value chains for secondary CRM production to identify and separate these waste materials from other waste materials. In the following paragraphs waste streams with direct recycling potential is described.

3.1.2 Nordic waste streams with direct recycling potential

The theoretical CRM recycling potential for a selected group of Nordic waste streams have been estimated based on available data. These waste streams include:

- Printed circuit boards
- Other WEEE
- Batteries
- Bottom ash from incineration of municipal waste
- Fly ash from incineration of municipal waste
- Ash from incineration of bio waste
- Shredder residue
- Tyre waste
- Tailings
- EAF slag
- EAF dust
- Ferro Alloy industry
- Nickel industry
- Copper industry
- Zinc industry
- Aluminium industry
- Silicon industry
- Other industries
- Alum Shale

Based on available data the theoretical recovery potential for individual CRMs from these waste streams were calculated. This recovery potential is summarised in figure 3.2.

	World market		Nordic consumption	WEEE	Batteries	Ashes	Cars & tires	Tailings	Iron / steel	Non-ferrous	Other
REE	280 266 t	25%	5 028 t	614 t	161 t	961 t	209 t	7 866 t	930 t	327 t	2 755 t
PGM	518 t	25%	9 t	16 t		2 t	28 t	0 t	0 t	33 t	0 t
Refractory metals (Re, W, Mo, Nb, Ta)	607 078 t	25%	10 891 t	91 t	1 t	1 138 t	335 t	693 t	1 009 t	1 686 t	91 t
Tech metals (Ga, Ge, In, Hf, Be)	2 726 t	25%	49 t	28 t	1 t	99 t	21 t	98 t	103 t	201 t	12 t
Cu Copper	30 576 000 t	25%	548 533 t	32 690 t	1 287 t	17 364 t	17 073 t	65 800 t	993 t	6 977 t	520 t
Co Cobalt	235 600 t	25%	4 227 t	182 t	1 606 t	191 t	155 t	42 026 t	107 t	702 t	31 t
Li Lithium	133 900 t	25%	2402 t	24 t	411 t	502 t	358 t	262 t	50 t	556 t	231 t
Mn Manganese	20 200 000 t	25%	362 388 t	77 t	1 868 t	28 977 t	1 697 t	195 344 t	29 871 t	5 292 t	153 t
Ni Nickel	6 765 000 t	25%	121 364 t	430 t	1 858 t	1 172 t	378 t	43 248 t	3 315 t	3 995 t	79 t
V Vanadium	125 000 t	25%	2 243 t	8 t	0 t	342 t	32 t	8 278 t	3 957 t	248 t	273 t
Bi Bismuth	21 000 t	25%	377 t	30 t	4 t	172 t	3 t	16 t	546 t	139 t	8 t
Sb Antimony	280 000 t	25%	5 023 t	191 t	2 412 t	1 278 t	193 t	87 t	668 t	794 t	28 t
As Arsenic	37 710 t	25%	677 t	18 t	60 t	473 t	669 t	19 170 t	611 t	2 152 t	557 t

Waste categories: WEEE, Batteries, Ashes, Cars & Tires, Tailings, Iron / Steel, Non-Ferrous, Other

Updated 05. Dec. 2023

Figure 3.2 Estimated amounts of theoretically recoverable CRMs from selected Nordic waste streams. Illustration Bergfald Miljørådgivere.

Figure 3.2 represents an attempt at quantifying CRM-recycling potential from Nordic waste streams and should be considered a rough estimation due to an uncertain and incomplete data base. To minimize the row number some CRMs have been grouped together. To limit the number of columns, some waste streams have been added together. For reference the size of the world market for each CRM or CRM-group have been included, and the Nordic share is shown as a bar from which the CRMA 25% recycling target is drawn through the following columns as a red dotted line. The theoretical recovery potential for respective CRMs or CRM-groups from each waste stream can be read as the height of the bar relative to the red dotted line. The theoretical recovery potential represents a 100% recovery rate. This is not realistic for almost all recycling processes. A more realistic recovery potential from each waste streams will be significantly lower than indicated in figure 3.2. To calculate a realistic recovery potential however require knowledge of which recycling process that are chosen, and which efficiency this recycling process will operate at. This will be unknown until a decision on how a waste stream will be recycled is made. For many waste streams, like incineration ashes and some tailings, the CRM concentration will also be so low that recycling will be challenging.

Added together the theoretical CRM-recovery potential for all CRMs from all waste streams in figure 3.2 amounts to about 900 000 tons. Figure 3.3 shows the relative share of individual CRMs.

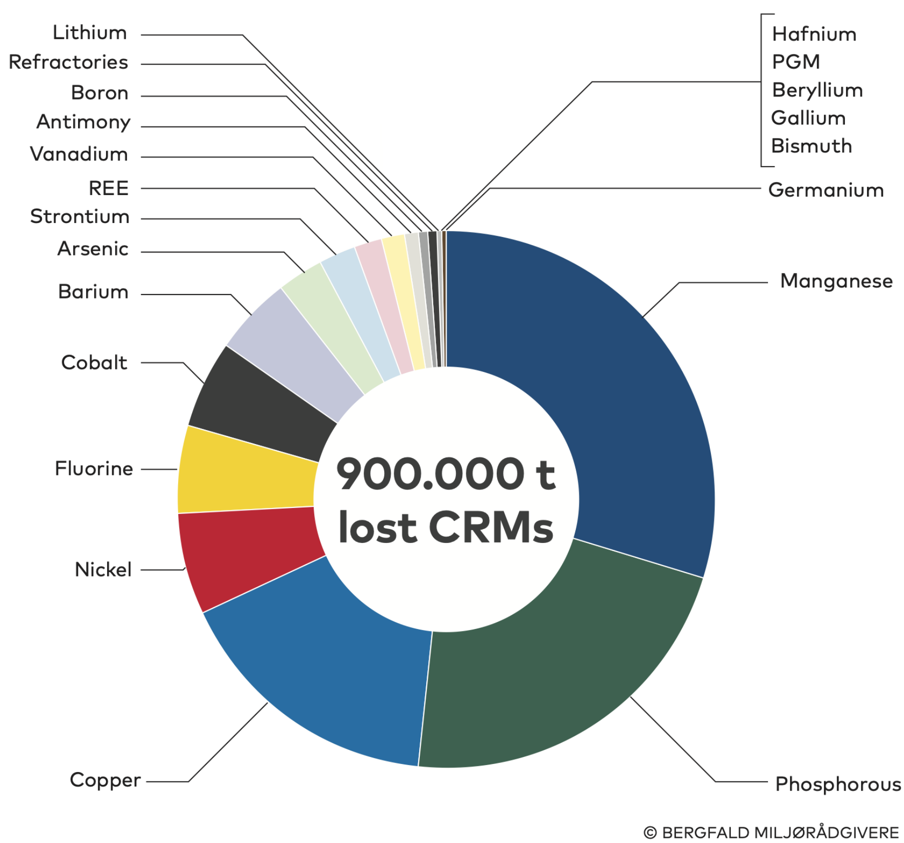


Figure 3.3 Relative share of recyclable CRMs from Nordic waste streams. Source and illustration: Bergfald Miljørådgivere

The theoretical CRM recovery potential is a function of the size of the waste stream and the corresponding concentration of individual CRMs in the waste stream. This means that a waste stream can contain significant amounts of CRMs although the concentration of these CRMs is low, if the waste volume is large enough. In the same way waste streams with high concentrations of CRMs may be of little importance if the total waste volume is negligible. As an illustration of this situation figure 3.4 shows the theoretical recovery potential of a selection of CRMs from waste streams described in 3.2. The size of the individual waste stream is illustrated by the heap that represent it, and CRM-concentrations are illustrated by the height of the bars that represent them.

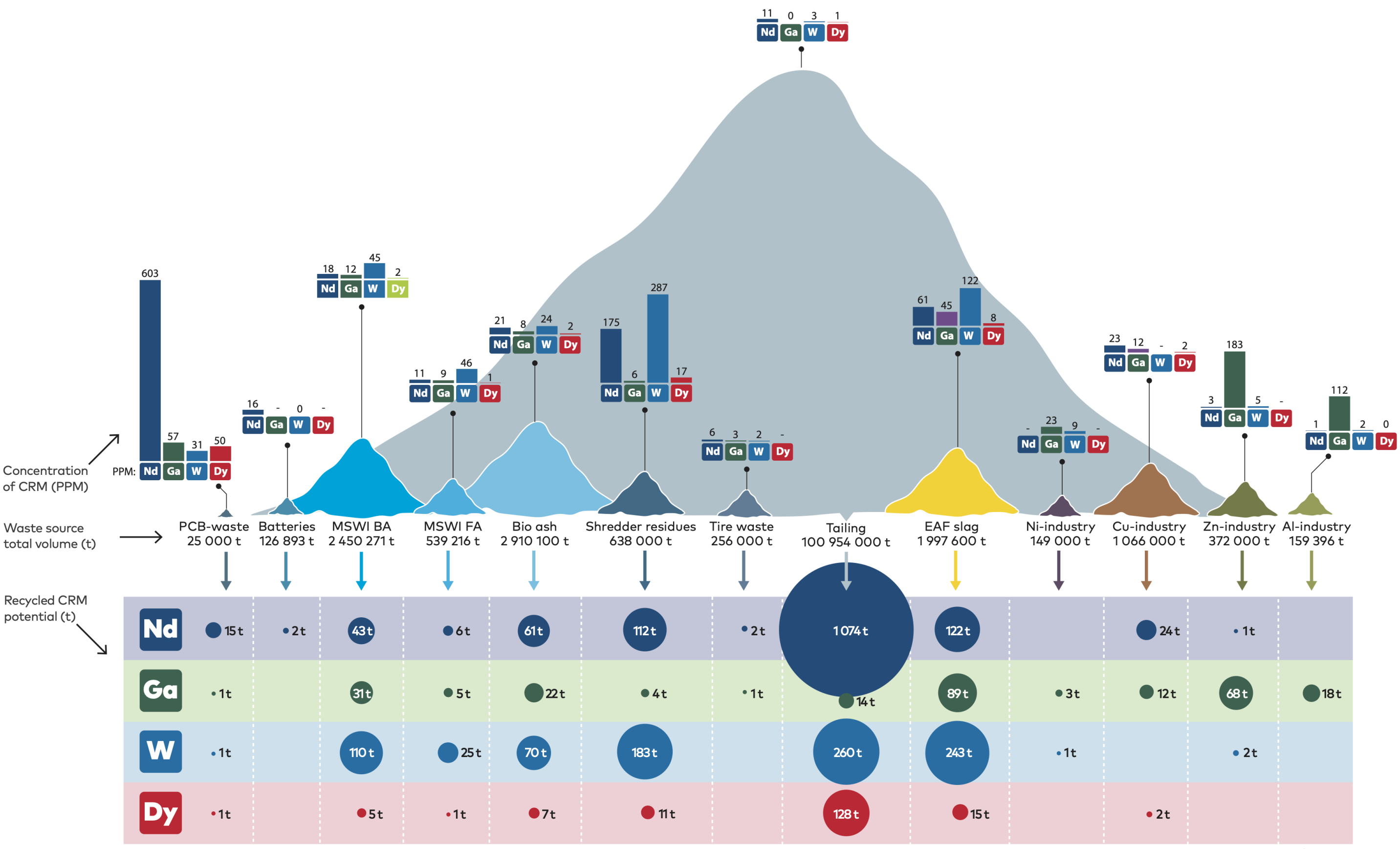


Figure 3.4 Waste streams with CRMs vary in tons and grades.
Illustration Bergfald Miljørådgivere.

4. Better collection and sorting of CRM waste in the Nordics

If a feedstock of recyclable waste material is not available, no recycling of CRMs is possible. Before any recycling of CRMs can take place three essential processes must therefore have taken place. First, relevant waste streams that contain recyclable levels of CRMs must have been identified. Second, a system for collection of these waste streams must be in place that allow the waste to be gathered and moved to its processing locations. Third, if the CRM-enriched waste material is mixed with other materials a separation process must be able to isolate the CRM-enriched materials from other materials.

Although the CRM-content in different waste materials can be easily described through chemical analysis, there is no complete description available of Nordic waste streams with recoverable CRM.[20] Any program for collection of waste that contains CRMs should therefore start with mapping CRM-levels in major waste streams.

All Nordic countries have already implemented collection schemes that isolate important waste streams including WEEE and batteries, scrapped vehicles and tyres. Although some recycling of CRMs from these waste streams take place, current treatment of these waste streams provides several barriers to increased recycling rates that are described in the next section. Sorting of waste is time consuming and presents health risks if manual labour is applied. Automatic sorting solutions should therefore be sought both for safety and cost efficiency reasons.

A discussion on how a collection system for recyclable CRM-waste can best be developed should start with an analysis of existing collection systems for other waste, as a collection system for CRM-waste must be successfully integrated with other collection systems to be rational and cost effective. An overview of existing waste collection systems and EPR-schemes in the Nordics is provided in Appendix 4.

To establish a system that make CRM-enriched waste available for recycling the following milestones must be reached:

20. This is however a requirement in CRMA

Figure 4.1 Necessary milestones in establishing a system that make CRM-enriched waste available for recycling.
Illustration Bergfald Miljørådgivere.

4.1 Barriers to better collection and sorting of CRM waste

The following paragraphs try to summarise significant barriers to a more efficient collection and sorting of Nordic CRM-enriched waste in the current situation as of 2023.

A systematic and complete description of CRM content in relevant waste streams does not exist.

Tailings from mineral processing and industrial slag, dust and sludge are examples of large and homogenous waste streams that sometimes contain high levels of CRMs. Because these waste streams occur in large amounts at a single point, they are often also more easily collectable. Available information about the chemical composition of tailings and industrial waste is often limited, which can make it difficult to identify waste streams relevant for CRM-recycling processes. The same challenge exists regarding materials in building stock and infrastructure, leading to potential recycling opportunities being overlooked during decommissioning.

CRM-enriched waste is landfilled in a way that limits future excavation options for recycling purposes.

Much CRM-enriched waste that could potentially be recycled is landfilled in a way that makes excavation of this waste for later recycling processes more difficult than it could have been. Tailings from mining operations are sometimes placed under water or stored underground in a way that restricts future access. Slag, dust and sludge from smelters and metal refineries are sometimes also placed underground in ways that create similar access challenges. When landfilled in open pits, CRM-enriched waste is often mixed with other waste streams and distributed at different locations. As an example, CRM-enriched residue from shredding of scrapped vehicles and WEEE are often landfilled together with other waste streams. Because there are often limited records of where different waste fractions are landfilled, identifying spots where CRM-enriched materials can be excavated can therefore be difficult. In some cases, waste streams are also stabilized in cement or other inert chemical structures to limit leakage of toxic compounds which will present additional challenges for future recycling projects. One example of this is the landfill for hazardous waste at Langøya outside Holmestrand in Norway, where hazardous inorganic waste that also contains CRMs is stabilized in gypsum before being landfilled.

Products are designed and assembled in a way that disrupt efficient sorting of CRM-enriched materials.

Many products are designed in a way that present a barrier to efficient separation of CRM-enriched materials from the remaining parts of the discarded product. When products are glued or welded together in ways that make decomposition and isolation of relevant components difficult or impossible without shredding or crushing the product, recyclable components cannot be retrieved for recovery. This is a common problem for WEEE where batteries, printed circuit boards and magnetic materials cannot be separated form products because they cannot be easily opened.

Buildings and infrastructure are constructed in a way that make extraction of CRM-enriched components and materials during decommissioning difficult.

CRMs are used extensively in building materials that may be used as feedstock for recycling when buildings and infrastructure are decommissioned. CRM-enriched materials are often mixed with other materials or diluted in a way that make selective sorting of recyclable materials difficult. Some CRMs are bound in unidentified alloys or captured in low concentrations in concrete from where it cannot be extracted. Some CRM-containing materials may also be mixed with toxic materials, or stuck to or tangled with matter that prohibits sorting out.

CRM-enriched waste streams are lost in cement and ceramic materials.

Many CRMs end up in cement or ceramic materials either as added ingredients like filler or pigments or as unintentional biproducts during cement production. CRMs added to cement that later becomes concrete become highly diluted and tightly bound in the surrounding chemical structure, making recycling later impossible or very difficult.

CRMs are lost in drain water.

Landfilled materials that are exposed to water may leach soluble CRMs that are then carried away in the drainage. From a tailing dam such leakage may amount to several tons each year as illustrated by the losses of nickel and other metals from the Talivaara mine in Finland that have caused large environmental damage. Similar leakage on a smaller scale may occur from shooting ranges. One of the largest CRM-loss however is probably phosphate lost through wastewater from agriculture, aquaculture and food industries. CRMs are also continuously lost as dissolved material in low concentrations in wastewater from industry and households.

Non harmonized standards for collection and sorting of waste in different municipalities and regions.

No common harmonized standard for collection of waste exists in the Nordics. A different number of sorted waste fractions are collected from households in different regions, and waste fractions collected from households rarely overlap with waste fractions collected from businesses and industry. Finland, Denmark and Sweden seem to have overall collection schemes that are more streamlined compared to Norway and especially Iceland, although some municipal differences in collection practice is tolerated in all countries. Lower number or differences in material composition of collected waste streams and less advanced sorting systems leads to larger amounts of mixed waste streams which distorts the potential for effective isolation of CRM-enriched waste materials.

No governmental incentives or requirements for collection of CRM-rich waste streams.

Although some Nordic countries like Finland and Denmark have set minimum standards for which waste streams that must be sorted, no country have established collection and sorting standards for CRM-enriched waste streams, except for phosphate.[21] There are also few if any incentives or support systems to cover additional operational costs that such practice may entail.

Some sectors are not included in collection and recycling schemes.

Collection of certain waste types are organized through Expanded Producer Responsibility Schemes (EPR-schemes). These schemes finances and organizes

21. As part of value chains for biogas production

collection and recycling of many waste streams in the Nordics including WEEE, batteries, vehicles, tyres and packaging. Some sectors are however omitted from EPR-schemes which creates uncertainty regarding how waste from these sectors is dealt with. Aviation, shipping, railways, military, space programs, nuclear power plants and the medical sector are examples of sectors that are omitted from one or several existing EPR-schemes. For many of these sectors there may be justified reasons for omitting waste streams from conventional waste treatment standards. Medical and nuclear waste presents exceptional hazards to human health and environment that limits recycling options. Military waste contains technology that must be protected against espionage etc. It may be assumed that when high technology applications of a sensitive nature are discarded, these applications are returned to the producer, although to what extent recycling of CRMs occur is difficult to know.

EPR-schemes only partly separate CRM-materials for recycling.

EPR-schemes for WEEE, batteries, vehicles and tyres include waste streams with significant amounts of CRM. Existing sorting routines only partly isolate these CRM-enriched materials and components for recycling. From WEEE magnets are often not removed from discarded products before shredding, and WEEE from scrapped vehicles is often not picked out before shredding, leading to significant loss of CRM-materials that could otherwise have been recycled.

Some EPR schemes refuse CRM-enriched waste that could have been recycled.

Some EPR schemes, for instance glass and metal in Norway, only accept waste materials from packaging, and refuse similar waste materials from other applications that could easily have been recycled through the same system. This limits the recycling volume of these EPR-schemes.

Challenges with increasing number of sorted waste streams.

Future recycling of CRMs may be able to rely on more detailed sorting of waste at its origin. Although sorting of waste into an extended number of waste fractions is possible, this comes along with additional costs and practical challenges. In densely populated areas and industrial zones with high activity available areas for additional sorting and storage of waste is often limited.

In regions with low population density and large distances, additional transportation costs may be relatively higher compared to regions with higher population densities.

Collected waste with recoverable CRMs is not delivered to recycling.

Although waste with recoverable CRMs is collected and sorted, this alone does not guarantee that these waste streams are recycled. Waste collectors and scrap dealers are not always familiar with existing options for CRM recycling. Sometimes recyclers are not able to compete with prices for alternative waste treatment like incineration or landfilling, and waste streams that could have been recycled are sent to other end treatments. There is also an increasing concern regarding criminal plundering of WEEE and scrap metal storage facilities. Illegal looting of high value WEEE is known to not only limit CRMs available for later recycling, but also to reduce the profitability of later recycling.

No robust and flexible technology for advanced automated sorting and defragmentation of WEE and other complex waste streams is available yet.

Extraction of CRM-enriched materials from many waste streams require extensive sorting and defragmentation. WEEE and scrapped vehicles are examples of waste streams where isolation of many CRM-containing components require extensive efforts and costs. Automatic sorting with intelligent robots may be a cost-effective way to deal with this challenge. Although automatic sorting robots with limited capacities exists, no robust and flexible technology for advanced automated sorting and defragmentation is available yet. This means that detailed extraction of CRM-enriched waste materials can only be achieved through manual labour. Increased manual labour incurs additional costs, and human health risks as both WEEE and scrapped vehicles are known to contain hazardous materials. Necessary precautions in terms of protective measures and monitoring of the working environment are therefore crucial measures that must accompany any manual labour use in sorting of these waste streams.

Magnets are difficult to separate from other materials.

Magnets present a unique challenge to sorting systems as they not only cluster together in lumps but may also will stick to magnetic metal surfaces in the sorting machinery. This may lead to clogging of conveyor belts and inside containers and metal covers. Most magnets are also very small and located at different and often inaccessible places in many products.

European recycling industries loses much CRM-enriched material through questionable export mechanisms.

Waste treatment is associated with high costs, and unconventional disposal methods will therefore always represent a tempting alternative for waste operators looking to cut costs by any means. Although waste export to countries outside EU is restricted and highly regulated in the Nordics, CRM-enriched waste exports of a questionable nature do occur. There are also examples of discarded EE-products being exported for reuse in developing countries that are shown to end up as waste without acceptable end treatment shortly after.

Phosphate from bio-residue from biogas production is not utilized as fertilizer for new plant growth.

Not all biogas plants have local surroundings where phosphate enriched bio-residue from the biogas production can be easily utilized as fertilizer. The high-water content of the bio-residue also limits the effective distance this resource can be transported. For this reason, not all phosphate in biogas production is recycled for new food production.

Loss of CRM in spent drilling fluids.

Offshore drilling fluids contain weight material often in the form of baryte that is listed by EU as a CRM. When the drilling fluid is discarded, this material is lost either as a discharge to sea, or when the solid material from the fluid is landfilled.

Conflict with existing regulation that limits CRM-recycling options.

Many non-CRM considerations already drive Nordic waste policies and justifies existing collection schemes and recycling options. One example is the need for safe and secure disposal of hazardous waste that often limit recycling options.

5. Better recycling of waste containing CRMs

If necessary feedstock for recycling of CRMs is available, two main conditions must be met for successful recycling to take place as illustrated in figure 5.1.

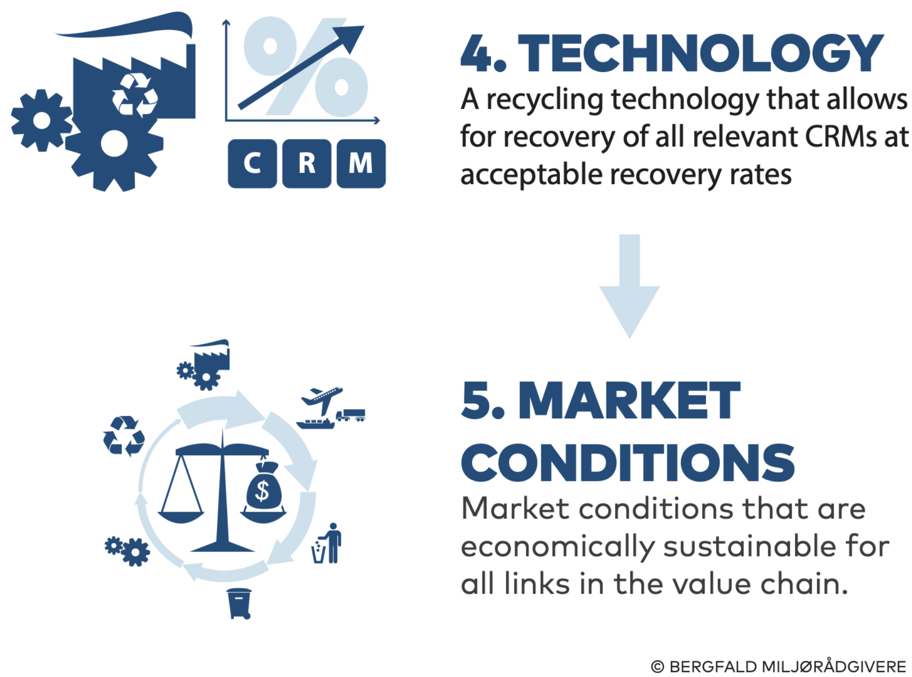


Figure 5.1 Necessary conditions for successful recycling of CRMs. Illustration Bergfald Miljørådgivere.

There are many technologies that can be used for recycling of CRMs, and they can be grouped into four main categories as illustrated in figure 5.2. Relevant waste streams for each main recycling option are also indicated.

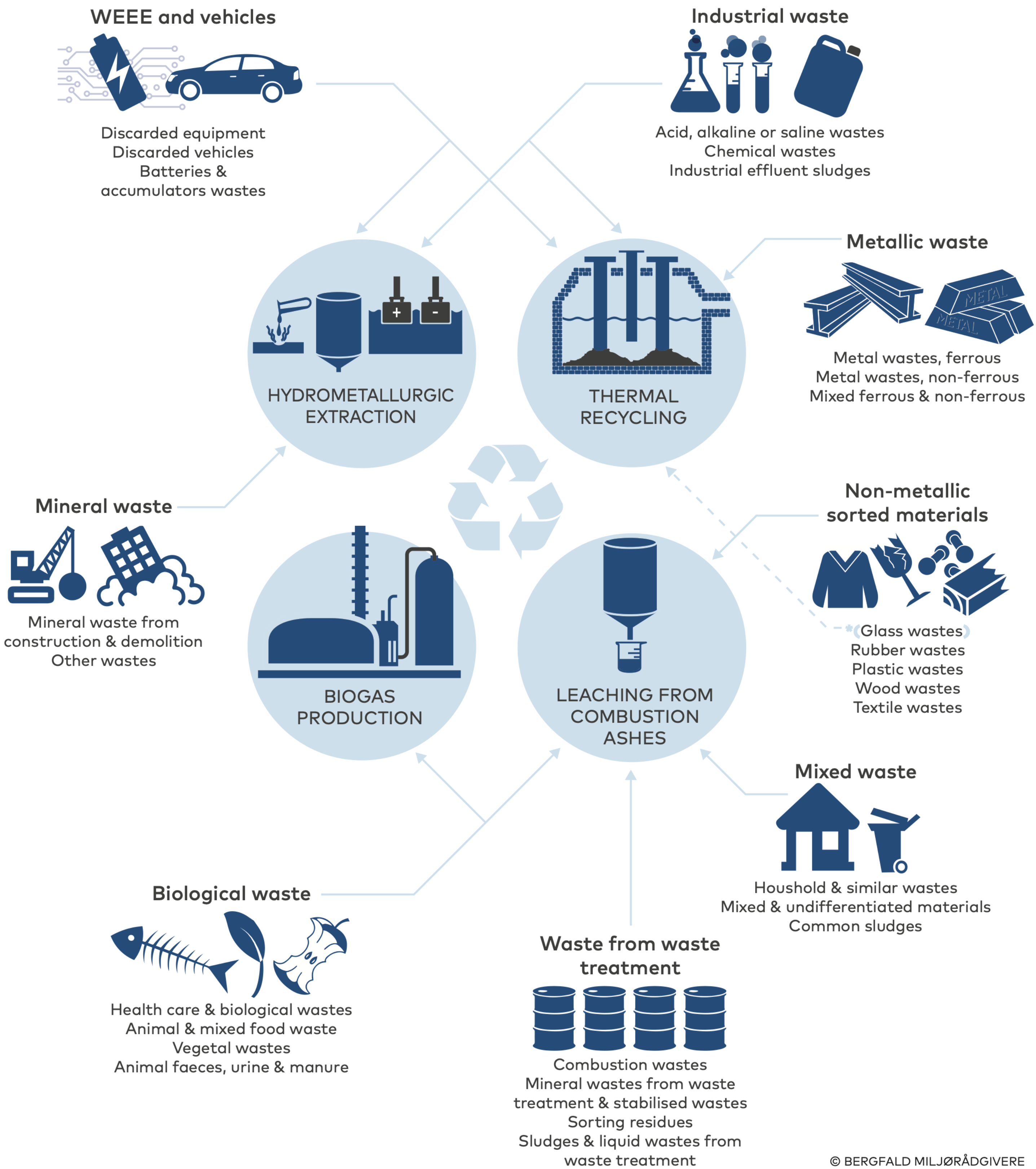


Figure 5.2 Main technological CRM-recycling options.
Illustration Bergfald Miljørådgivere.

5.1 Recycling of CRM-waste in the Nordics

This section describes to what degree individual CRMs are recycled in the Nordics, and summarizes key industries that either currently recover CRMs or have technological advantages when it comes to establishing new or expanded CRM-recycling

Aluminium/bauxite

Aluminium is recycled as metal and alloy, and aluminum oxide is downcycled to clinker. There is no recycling of bauxite, and neither should there be, as this mineral has no applications except as a raw material for primary aluminium.

Speira[22] in Norway has two plants receiving complex slag and dross from both primary and secondary aluminium plants, wastes that contain a multitude of CRMs. Indeed, it is possibly easier to add extraction and refining units to this plant than to install similar plants on each of the many smelters.

Antimony

There is to our knowledge no dedicated recycling operations in the Nordics for antimony. As antimony is commonly used as alloying element in lead, it is indirectly recovered when lead is recovered. In the Nordics this happens at the Boliden Bergsøe plant in Landskrona and at Sala Bly in Sweden.

Arsenic

There is to our knowledge no relevant recycling of arsenic in the Nordics. There are dedicated incineration plants for CCA-waste, which brings forth a waste with high arsenic content. The arsenic-loaded ash is landfilled as hazardous waste and not recycled.

Baryte

There is to our knowledge no relevant recycling of baryte in the Nordics. There are waste treatment facilities for discarded drilling fluids, but these are concerned with reducing environmental footprint of the waste, not recycling the barium, although some barium containing drilling fluids may be reused.

Beryllium

There is no recycling capacity for beryllium or beryllium-containing alloys in the Nordic countries, neither in EU/EEA. WEEE sorting schemes are systematically sorting out beryllium-containing components during WEEE dismantling, but all of this is delivered as hazardous waste. The closest recycling capacity, to our knowledge, is Japan. There are industrial operations also in Kazakhstan and USA, but attempt to reach those with supplies of beryllium WEEE scrap from Europe have consistently failed.

22. Bergfald Environmental Consultants is a HSE/permitting consultant to Speira.

Bismuth

There is to our knowledge no recycling capacity for postconsumer bismuth or bismuth-containing materials in the Nordic countries.

Boron

There is to our knowledge no relevant recycling of boron in the Nordics, nor in EU/EEA.

Copper

There is a huge capacity for copper recycling in the Nordics. The Boliden plant in Skelleftå is by far the most important. Indeed, most of copper containing WEEE scrap is currently sent there for recycling. There are also other possibilities for recycling, both in the Nikkelverk plant in Norway and the Boliden plant in Harjavalta.

Cobalt

There is a sufficient capacity of downstream cobalt recycling in the Nordics, if cobalt in the future is recovered from wastes. From the refining and smelter side, there is the Nikkelverk plant in Norway and the Boliden plants. From batteries, the lithium-ion-battery recycling plants are taking out black mass containing cobalt that in the future will be recycled in these refineries.

Feldspar

Sweden, Finland and Norway extract feldspar through the companies Sibelco and North Cape, but except for some glass recycling, no recycling operations are known to take place in the Nordics.

Fluorine

There is to our knowledge no relevant recycling operations for fluorine in the Nordics. However, that could be possible to develop. There is an aluminium fluoride production plant in Odda, Norway, currently owned by the Fluorsid group, based on imported fluorspar from Morocco. Wastes with high level of fluoride could in principle be processed at this plant. To achieve that, the plant needs an updated operational permit, and the fluor-containing waste needs to be properly characterized to avoid contamination of the products. Indeed, preprocessing might be needed. Capacity-wise, this plant would probably be able to absorb any tonnage that can be extracted from Nordic waste fractions.

Gallium

There is no recycling capacity for postconsumer gallium or gallium-containing alloys in the Nordic countries, nor in EU/EEA. There are gallium recycling operations for ingot scrap in Germany, but the requirements there are unreachable for any kind of scrap and extracts possible to produce from Nordic waste.

Germanium

There is no recycling capacity for postconsumer germanium or germanium-containing alloys in the Nordic countries. There is a recycling plant for high concentration germanium sludges in Belgium. That plant is currently idle, as all germanium-rich fractions are sent to Russia and China.

Graphite, natural

There is recycling capacity for postconsumer lithium batteries in the Nordics. These plants are currently focusing on extracting the metals, such as nickel and cobalt. However, they represent an infrastructure that could make recycling of graphite possible. However, the need for graphite in other industries, such as cast iron, is high, so downcycling is also an opportunity.

Hafnium

There is no recycling capacity for postconsumer hafnium or hafnium-containing alloys in the Nordic countries. There has been some low-volume hafnium processing on-and-off in France.

Helium

There is no recycling capacity for postconsumer helium in the Nordic countries, but it will be rather straightforward to establish recycling solutions for spent waste gas. There are established return systems for helium bottles, and systems for the collection and processing of gases could be expanded.[23]

HREE

There is no recycling capacity for postconsumer HREE or HREE-containing materials in the Nordic countries, nor in EU/EEA. Currently, there is only limited capacity in China. There is a plant under construction in USA for the processing of virgin HREE, but that will not be easily available for Nordic or European countries. There is also a LREE-processing plant under construction in Norway, which can be expanded to recycle HREE if provided incentives to do so.[24]

Lithium

There is recycling capacity for post-consumer lithium batteries in the Nordics. So far, these processes do not recover lithium, but focus on extracting metals such as nickel and cobalt. However, the infrastructure for recycling of lithium is established. Recycling technology from batteries that include lithium is expected to be commercially available in the near future.

LREE

There is no recycling capacity for postconsumer LREE or LREE-containing materials in the Nordic countries, nor in EU/EEA. There have been plants in the recent past,

23. www.returgass.no/
24. Disclosure: One of the report authors is a minority shareholder in the REEtec plant.

for example in France, Belgium, Germany, Italy, Spain and Austria, recycling specific LREE containing materials. As neither of these plants have received legal or financial support to protect them from market manipulation, they have all closed. There is a virgin material LREE-processing plant under construction in Norway, and it can be expanded to recycle LREE if provided incentives to do so.[25]

Magnesium

There is no recycling capacity for post-consumer magnesium in the Nordic countries. There is a substantial European capacity for recycling both sorted magnesium components and industrial scrap. Until 2005, there was a recycling operation in Norway for complex magnesium scrap, able to handle a wider range of waste than what is currently available in Europe. This plant is currently idle and possible to restart – given the right incentives. There is a substantial consumption of magnesium as an alloying element in the Nordic aluminium and steel industries of more than 20,000 tons that could have been converted from primary to secondary magnesium – if the necessary incentives were provided, this could reduce dependence on the current three primary magnesium suppliers to Europe; China, Russia and Israel.

Manganese

There is some industrial recycling capacity for manganese in the Nordics. The Eramet and Ferroglobe manganese alloy plants have the possibility to receive high-manganese wastes as feedstocks. Indeed, they are currently operating advanced dust/fines recycling operations and can receive much more. Stavanger Staal in Norway is recycling high manganese steels. There are also plans to establish a manganese sludge recycling plant in a Scandinavian country.

Nickel

There is a huge capacity for nickel recycling in the Nordics. The Nikkelverk plant in Norway and Boliden plant in Harjavalta are both able to receive high-nickel feedstock for recycling. Indeed, both have declared their intention to increase the secondary feedstock supplies if such materials become available.

Niobium

There is no recycling capacity for postconsumer niobium or niobium-containing materials in the Nordic countries. There are several stakeholders trading and processing minor volumes of high-niobium materials in EU.

PGM

There is substantial recycling capacity for PGM metals in the Nordics. The Nikkelverket plant in Norway, Boliden Rönnskär in Sweden and Boliden Harjavalta in Finland are all able to receive different PGM-containing secondary feedstocks for

25. Disclosure: One of the report authors is a minority shareholder in the REEtec plant.

processing, even low-grade materials. The K.A. Rasmussen plant in Norway is able to process high grade metals such as industrial catalysts.

Phosphate

The most developed method for recycling of phosphate seems to be through biogas production where the nutrient-rich residue from the anaerobe digestion process can be used as phosphate rich fertilizer. All Nordic countries have extensive biogas production. There are also interesting projects extracting phosphate from incineration ashes and wastewater.

Scandium

There is no recycling capacity for postconsumer scandium or scandium-containing materials in the Nordic countries, nor in the Western hemisphere. Both primary and secondary scandium need processing in either Russia or China.

Silicon

There is no recycling capacity for postconsumer silicon or silicon-containing materials in the Nordic countries. There is ongoing research and tests for recycling of certain high-end silicon products, such as solar panels. Indeed, substantial such work has been carried out at the Elkem/REC test center in Norway. However, as it was recently decided to close the two Norwegian REC plants, recycling is not expected to be industrialized. The Wacker plant in Norway may consider recycling opportunities in the future, but no timeline has been provided.

Strontium

There is no recycling capacity for postconsumer strontium or strontium-containing materials in the Nordic countries.

Tantalum

There is no recycling capacity for postconsumer tantalum or tantalum-containing materials in the Nordic countries. However, there is advanced processing capacities in Estonia and Germany that could easily be expanded if extraction of tantalum containing wastes in the Nordics is started.

Titanium

There is no recycling capacity for post-consumer titanium or titanium-containing materials in the Nordic countries. There is from time to time the use of titanium metal turnings in the production of primary aluminium alloys. However, this is industrial scrap, a globally traded byproduct. Currently, all titanium metal consumption in the Nordics is based on imported material from China or Russia.

Tungsten

There is significant recycling capacity for tungsten waste, organized by Swedish company Sandvik. The key recycling furnace is in Austria, but Sandvik operate a high-quality collection scheme and reclaiming operation in the Nordics to get feedstock. If tungsten recovery from WEEE or slags are increased, this value chain would be valuable to cooperate with.

Vanadium

There is no recycling capacity for postconsumer vanadium or vanadium-containing materials in the Nordic countries. Neometals in Finland have a project to upgrade vanadium-containing blast furnace slags currently produced and landfilled in Sweden and Finland to a commercial ferrovanadium alloy. The project has received funding from the European Investment Bank as a strategic project. If built, this plant will probably be able to receive also other high-vanadium waste streams.

5.2 Barriers to better recycling of CRM waste

Many CRMs are distributed in products and materials at low levels that make recycling challenging.

Although CRMs are chemical components of many waste streams, the concentrations are often too low for profitable extraction. Many applications of CRMs like pigments, catalysts and additive in glass and ceramics require only small amounts in each product. High prices and uncertain supply chains also limit the use of many CRMs. Although large amounts of CRMs are consumed in the manufacture of products and materials due to large overall product volumes, a limited number of waste streams arise containing high concentrations of CRMs that can be easily recycled. CRMs are also often bound strongly in chemical structures that make extraction even harder.

Large amounts of CRMs are also available in tailings from mining operations and in slag, dust and sludge from metal processing industries. Even so, the concentration of CRMSs is often low and not easily extractable.

Substitution with less valuable materials and micronization of components with increasingly heterogeneous chemical composition makes recycling less profitable.

High prices and concern over supply risks has led to substitution of many costly raw materials with less expensive ones, exemplified by increasing substitution of cobalt with less expensive nickel in batteries. There are also examples of shifts in technological applications where new solutions that replace older ones demand lower input of expensive materials, which is the case for data storage when conventional hard disks (HDD) are replaced with solid state drives (SSD).

In addition, the use of high value materials is becoming more efficient through micronization of many components which have led to reduced levels of high value materials in many products, especially in the EE-sector. From a resource efficiency standpoint this is a favourable development but creates a rising concern in the recycling sector where recycling processes create outputs with lower economical value. This conflict between more efficient product design and less profitable recycling may also lead to reduced economic incentives for recycling of CRMs.

Large amounts of CRMs are lost during metal recycling.

One main application of many CRMs is as additives in alloys. When these alloys are scrapped and recycled currently available technology often only allow for recovery of base metals while most minor metals are either lost in the slag or follows the recovered base metal as a pollutant. This is a significant challenge for recycling of both aluminium and steel, not only because important CRM-resources are lost, but also because CRMs that unintentionally follow the recycled steel or aluminium metal often lower the quality of the recycled material and restricts the use of secondary metal products.

PCBs contain more than seventy elements including a large number of CRMs. When gold and copper is extracted from PCB significant amounts of tantalum, gallium, germanium and rare earth elements are lost in the recycling process. Additional metals can be recovered with current technology but often at the cost of diminished recovery rates of the main metals.

No recycling technology is available for CRM-recycling from multiple feedstocks.

Although tailings, industrial slag, dust and sludge, together with other collected waste streams contain large amounts of CRMs, not all waste streams and not every individual CRM have currently mature technology options when it comes to recycling. This means that even if new recycling of certain CRMs were to be required through legal instruments or made economically incentivised, no process can still be designed to ensure efficient recycling. The development of mature recycling technologies for many CRMs will most likely take many years and require massive R&D-efforts.

Many applied technologies for recycling of CRMs operate with low recovery efficiencies and extract only a limited number of CRMs that are available in the feedstock. Improving the recovery efficiency of these processes is also a huge undertaking that cannot be expected to be solved quickly. However, there is a lot to learn from the established mineral processing industry. Companies active in processing of complex nickel or copper ores, such as Glencore and Boliden, are familiar with complex multiprocessing schemes to extract even very low grades of precious metals such as gold and PGM. The competence and technology developed by these companies have matured over decades. Indeed, even if the political will exist to significantly increase recovery of CRMs from complex and mixed waste streams, one should not underestimate the time and effort needed to develop this.

CRM-recycling is often less cost-effective than production of virgin CRMs.

Compared to extraction of CRMs from a mineral ore, recycling of the same CRMs from waste materials are often more costly due to more heterogenic feedstock and lower concentrations of CRMs. Gallium is for instance found as 100–300 ppms in dissolved bauxite liquor, but are only used as a few tens of ppms in most LED. Another example is germanium, which is typically found in +1000 ppms in lead and coal ash concentrates, but only used in a few tens of ppms in PCBs and special optics. In both cases there are components with higher grades but the bulk of the waste tonnage holds very low concentrations.

Small volumes and large fluctuations in prices make recycling of products containing CRMs economically challenging.

Although CRMs are essential chemical components of countless products and materials, many CRMs are only used in very small amounts in each product which limits the market size for the same CRMs. This creates challenges when scaling recycling processes to fit the market, and at the same time allow for a profitable production volume. In addition, the market price for many CRMs is historically known to be volatile and fluctuate in unpredictable ways that creates additional financial risks for a recycling operation.

Market manipulations from dominant CRM-suppliers disrupt European CRM-recycling.

A few countries have obtained market dominance when it comes to both extraction and processing capacity for individual CRMs and have used this position to disrupt downstream industries in other countries through market manipulations that include disputed export restrictions.

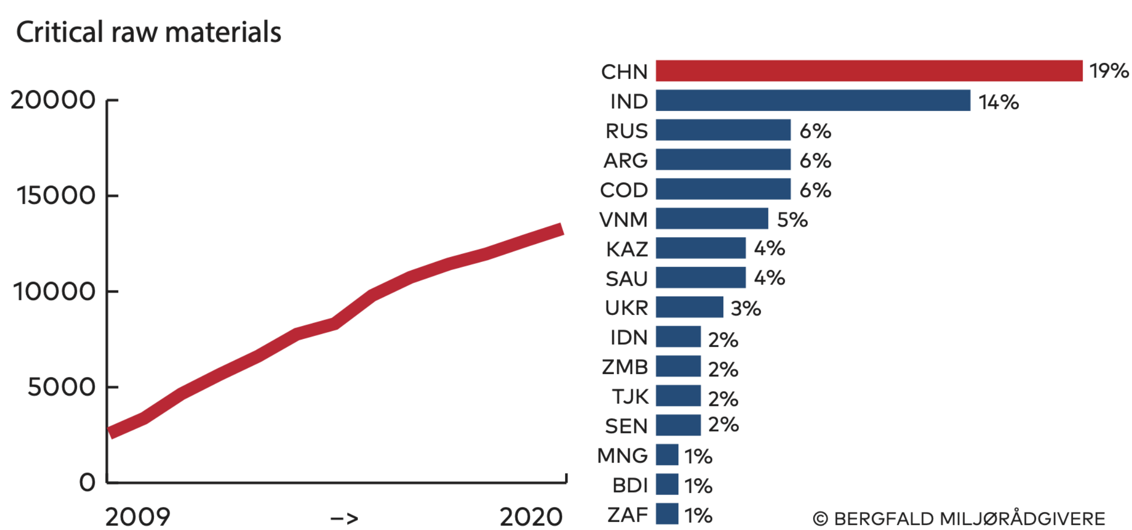


Figure 5.3 OECD is mapping export restrictions of critical raw materials.[26] As can be seen from the figure, the number of such restrictions are increasing. Illustration Bergfald Miljørådgivere.

26. OECD 2023. Raw Materials Critical for the Green Transition: Production, International Trade and Export Restrictions.

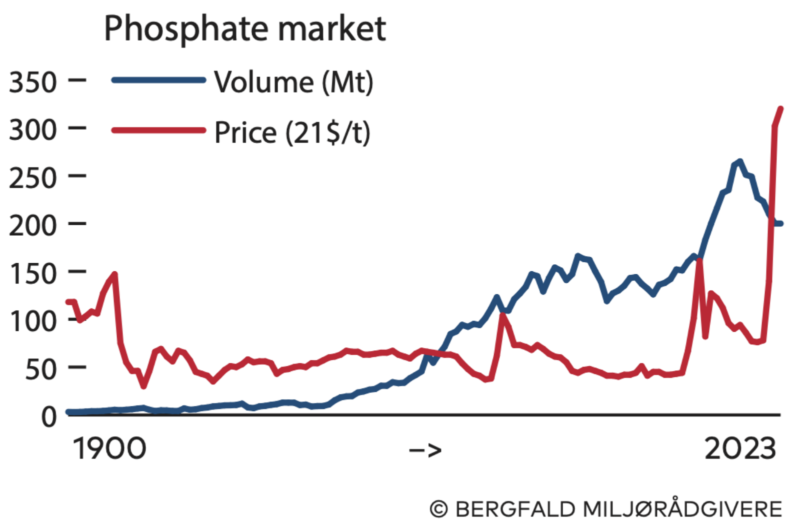


Figure 5.4 Global market size and prize for phosphate rock.
Source: Bergfald Miljørådgivere

NIMBY-responses blocks new CRM-recycling projects or necessary support infrastructure.

Increased CRM-recycling will require the construction of new process plants and industrial support facilities that can be expected to face significant resistance from local communities that are becoming increasingly hostile to new industrial projects in their own region. This phenomenon, often referred to as the NIMBY-effect (Not In My Backyard) is on the rise in many European countries, and may disrupt efforts to establish new CRM-recycling projects.

6. Measures and instruments for increased recycling of CRMs

This chapter discusses potential measures and instruments that should be considered when formulating a national strategy on how to reach the CRM recycling goals of EU, as stated in the CRMA. The main goal of this strategy should be to build robust value chains for recycling of individual CRMs, although building recycling capacity for all CRMs inside the Nordic countries is not considered to be realistic. Instead, a partnership for distribution of recycling responsibility for all CRMs should be sought with European countries outside the Nordics to ensure a necessary scale for the recycling capacity that can achieve cost competitiveness with similar industries outside Europe. The strategy should however aim at building systems for collection and sorting of recyclable waste streams for all individual CRMs in each Nordic country. The following five main milestones are considered critical to successfully build these value chains:

1. A system that makes it possible to identify waste streams with CRM-recycling potential.
2. A system for cost effective 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 recovery of all relevant CRMs at acceptable recovery rates.
5. Market conditions that are economically sustainable for all links in the value chain.

Since EU published the first CRM-list in 2011, other CRMs have been added, and national programs required by CRMA should take into account and provide a preparedness for further CRMs being added in the future. It is also important to take into account expected technology shifts that may change the CRM-composition of materials and products that follow these technology shifts.

While drivers are conditions that accelerate progress towards a milestone, barriers hinder or prevent the same development. Measures are actions taken to either support drivers or remove barriers. A general measure addresses all or a group of CRMs while specific measures only address a single CRM. Only general measures are described in this chapter, while CRM-specific measures can be found in the description of each individual CRM in Appendix 1. Expected impact, costs and cost efficiency are indicated for each described measure. These are rough estimates based on discretionary assessments and will to a large degree depend on how each measure is designed and implemented.

6.1 Pre-collection measures

National program for mapping levels of CRMs in relevant waste streams.

Identification of waste streams suitable for CRM-recycling requires at a minimum information about the chemical composition of the waste. For tailings and mineral waste, the residual levels of chemical components that are extracted as a product are normally well described, but information of other elements are often less well described or lacking. The same situation is also often the case for industrial slag, dust and sludge from metal processing and makes it difficult to evaluate waste streams with CRM-recycling potential. No program exists for systematic mapping of residual resources in other waste streams known to sometimes contain higher concentrations of CRMs, like shredder residues from scrapped cars and WEEE are either applied by the industry that create them or landfills where they are often placed. The same goes for ashes from waste incineration.

A national program for systematic mapping of CRM content in tailings, industrial slag, dust and sludge and CRM-enriched waste from metal processing industry and other relevant waste streams is essential for identification of waste streams that may be potential feedstock for CRM-recycling. The test program should include all CRMs and be done annually or every other year to capture changes in the chemical composition over time.

A mapping of available CRM-materials in buildings and infrastructure should also be considered.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

National statistics of significant CRM material streams showing both consumptions, collected waste and recycled CRM-volumes.

A formulation of efficient policies for better CRM-management requires an understanding of relevant CRM-containing material streams. To understand the movements of streams of CRM-enriched materials through society a statistical accounting of the total market consumption of CRMs and corresponding waste streams are necessary. Nordic countries already keep national statistics that account for amounts put on market of different products and different waste streams, but these statistics don't disclose material movement of CRMs. An updated statistical scheme that includes a description of individual CRMs movement through society from product to waste, will not only assist in optimizing policies, but also be a necessary tool for evaluation progress towards set recycling targets.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Restriction on use of CRM-rich materials in cement.

In production of cement, many different raw materials and energy carriers are used as feedstock, including several waste materials. Some of the waste materials used contain elevated levels of CRMs. When used as a feedstock for cement, these CRMs are diluted to very low concentrations and are chemically bound in a way that makes future CRM-recycling impossible or at best very difficult. The only way to avoid this loss of feedstock for future CRM-recycling is therefore to restrict the use of CRM-enriched waste materials as feedstock for cement production or other industrial processes that make the CRMs impossible to recover.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Ban or consumer tax on non-essential use of CRM.

Some CRMs are used for non-essential purposes, such as content in fireworks and as pigments in glass and ceramics and helium in balloons. By restricting the use of CRMs for non-essential purposes more CRMs will be conserved for use in more important applications. Alternatively, a tax on non-essential CRM could also restrict non-essential use of CRMs.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Market requirements for product design that support efficient identification and separation of CRM-enriched components and materials.

Although EU's eco-design directive requires design and construction of products to be done in a way that limits the environmental footprint of the product and includes resource efficiency and recycling issues to be addressed, no specific requirements regarding individual CRMs have so far been adopted. A specification of such requirements could help reduce the consumption of CRMs. Digital passport is another interesting concept that may be used to convey information about the CRM-content in the product to future collectors and recyclers.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Design and construction of buildings and infrastructure that support easy identification and separation of CRM-rich materials during future decommissioning.

Buildings and infrastructure are currently constructed without any concern for recycling of CRM-content in the construction materials. This means that materials are produced and assembled in ways that obstruct rational separation and sorting of CRM-enriched waste during the later decommissioning and demolition phase. Additionally, no information is available that makes it possible to identify construction materials with enriched with CRMs. Some effort should be put into evaluating to what degree production of building materials, architectural plans and construction practices can be updated in ways that make collection of CRM-enriched raw materials from construction and demolition waste more efficient.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	high

6.2 Measures for improved collection and sorting of CRM-waste

Separate collection and delivery of CRM-enriched waste for recycling.

A significant barrier to CRM-recycling is mixing of CRM-enriched waste with other waste materials. This issue can be handled by collecting waste streams that may be recycled for CRMs separately. This will normally add to the total waste management costs due to more complex transport and storage solutions. Mandated collection should therefore be considered either as a legal order or be built in as requirements in operation permits. Examples of CRM-enriched fractions that should be considered for separate collection are described in Appendix 3.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Landfill bans on recyclable CRM enriched waste.

Sometimes, recyclable CRM-enriched waste is landfilled because this is either less costly or convenient. A legal ban on landfilling of recyclable CRM-enriched materials can redirect these waste streams to recycling solutions.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

Mono-cell landfilling of CMR-enriched waste that cannot yet be recycled at well-marked locations in the landfill.

CRM-enriched waste, like industrial slag, dust and sludge for which there are yet no available recycling options, should be landfilled in a way that will facilitate later excavations when new technology makes this possible. This entails that relevant waste types are not mixed with other waste, but landfilled in well-marked mono-cells. If mining operations or metal processing industry are landfilling sub streams of waste that are especially CRM rich, these sub streams should also be landfilled unmixed in well-marked mono-cells. Landfill requirements should be specified as a part of the operation permit.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Mapping of available CRMs for recycling as part of all decommissioning and demolition projects.

Preparations before demolition of buildings and infrastructure already require a survey that identify hazardous materials that must be picked down and handled separately. These studies should also include a survey of waste streams that contain materials suitable for CRM-recycling.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Recovery of CRM from wastewater.

Wastewater from industry and households contain low levels of dissolved and particular CRMs. Although standard sewage and wastewater treatment include chemical or biological steps to remove some pollutants and nutrient salts, no similar practice exists for recovery of valuable resources including CRMs exists, except for phosphate. Some wastewater treatment companies like VEAS that operate Norway's largest wastewater treatment plant in the Oslo fjord have been exploring techniques for expanding the list of chemical compounds that can be removed from the wastewater. Technological options for recovering CRMs from wastewater should also be considered.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	low

Removal and sorting of components from printed circuit boards before recycling.

Printed circuit boards (PCBs) contain an array of CRM-enriched electrical components that differ in chemical composition. Conventional recycling of PCBs leads to loss of all but main CRMs in this waste material. If PCBs are stripped for components before recycling and each component is separated into different fractions this will allow for individual recycling processes that can capture a larger number of CRMs.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Consider EPR-scheme for non-WEEE CRM-enriched waste streams.

EPR-schemes have proven to be efficient arrangements to ensure efficient collection and recycling of selected waste streams. Although EPR-schemes already exists for some CRM-enriched waste streams like WEEE and scrapped vehicles, many CRM-enriched waste streams like ammunition, alloys and catalysts are not part of an EPR-scheme. EPR-schemes for additional selected CRM-enriched waste streams should be considered.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Upgrading EPR-scheme for waste regarding CRMs for WEEE, vehicles and tyres.

Although existing EPR-scheme for WEEE, vehicles and tyres facilitate efficient collection of these waste categories, there is still large room for improvement regarding separation and sorting of CRM-enriched materials for recycling. Magnets are rarely recovered; batteries are often left inside discarded products that cannot be easily opened and printed circuit boards are not stripped for components that should be recycled separately due to labour costs of manual sorting. For scrapped vehicles the situation is even more problematic as many electronic components are not removed at all before shredding for the same reason. Therefore, the framework conditions for these EPR-schemes should be updated to include mandatory separation of CRM-enriched components and materials that can easily recycled.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

CRM-recycling obligation for sectors that are omitted from EPR-schemes.

Some sectors are omitted from EPR-schemes which creates uncertainty regarding how waste from these sectors is managed. Sectors typically excluded from one or several EPR-schemes include aviation, shipping, railways, military, space programs, nuclear power plants and the medical sector. Although there may be well founded reasons for these omissions, sectors outside EPR-schemes should still be required to seek recycling options for CRM-enriched waste as far as this can be done in a safe and secure manner.

Another example of waste omitted from EPR-schemes is metal and glass that are not considered to be packaging. To ensure better recycling of non-packaging glass, including window glass, and metal should be considered for incorporation in an EPR-scheme.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

R&D program for development of better sorting technology.

Technology must be developed that allows more effective sorting of recyclable CRM-enriched components and materials. Examples include the need for robots and other automated sorting systems that allow for picking out individual components like capacitators and magnets for selective collection and further treatment together with more efficient separation of individual alloys. Another example may be more advanced sorting systems for aluminium alloys that allow separation of individual alloys.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

Mandatory sorting of magnets.

Magnets are difficult to separate from the products they are part of, partly because they are difficult to access, and partly due to their magnetic properties that create a stickiness problem where single magnets will cluster together with other magnets and cling to magnetic surfaces on conveyer belts and container walls. These challenges can only be overcome through manual sorting until automatic sorting systems become commercially available. By introducing legally binding sorting requirement for magnets for all waste sorting facilities that deal with waste streams that contain magnets, efficient and thorough recovery of magnetic materials from relevant waste streams can be established. This requirement can either be implemented in existing waste regulations or be incorporated in operational permits for relevant facilities.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Industrial sorting system for magnets constructed by non-magnetic material to avoid stickiness problem.

The magnetic properties of magnets are known to create a stickiness problem where single magnets will cluster together with other magnets and cling to magnetic surfaces on conveyer belts and container walls blocking or chocking the movement of other magnets. One way to deal with this challenge may be to construct a sorting line for magnets in non-magnetic materials like brass or aluminium.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Increased security measures to guard against illegal looting of high value materials in WEEE.

Large volumes of high value materials are illegally looted from sorting facilities that store waste that can easily be stripped for easy to carry high value components. These high value components will often also contain CRMs that are lost for later recycling when removed. Better security measures may lead to reduced looting problems.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

R&D program for capturing CRM streams before ending up in unrecoverable recipients.

Much CRM content is bound in waste streams that are currently being used as feedstock for production of cement or glass or other ceramic materials. CRMs that are captured 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 for extraction of CRMs from waste streams before this waste stream is being used as feedstock for such production processes should be examined.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Collection of CRM-enriched ammunition residues from shooting ranges.

Ammunition contain copper, antimony and sometimes bismuth. Collection of ammunition residues from shooting ranges will not only allow for these CRMs to be recycled but will also limit leaching of lead and other heavy metals from sediments at the shooting range.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Requirements or economic incentives for delivery of CRM-enriched waste to facilities that can recycle it.

When scrap dealers and waste collectors decide which final treatment collected waste will be sent to, costs obviously play a large part in this decision. Unless recycling options can compete with other waste treatment alternatives like incineration or landfilling, recyclable waste will often not be recycled. Regulatory requirements in operating permits, legal instruments or economic incentives may therefore be necessary to ensure that recyclable CRM-waste streams collected by a waste operator really is really recycled.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Information service that provides an overview of available recycling options for CRM-enriched waste.

All scrap dealers and waste management companies cannot be expected to keep up to date on all available recycling options. Lack of knowledge about available recycling options may lead to recyclable CRM-enriched waste being sent to other end treatments. An information service that gives an updated and complete overview of available recycling options for CRM-enriched waste may be useful in this regard. European waste industry is complex which means that it is not certain that all waste operators have sufficient knowledge of all available recycling options to be able to identify good recycling options for CRM-enriched waste.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

Updating national regulations that restricts CRM-recycling.

CRM-recycling has so far not been a high concern when formulating regulatory demands for industry. National regulations and industry requirements may therefore contain regulatory barriers to better CRM-recycling.

Currently, there are significant restrictions on processing of and recycling from wastes classified as hazardous. Historically this have been justified by considerations for health, safety and environmental protection, and these concerns are obviously still just as valid. However some hazardous waste do contain high levels of recoverable CRMs and if these waste streams can be recycled without unacceptable risks then unnecessary regulatory barriers shouldn't prevent this.

As an example, gallium, germanium and indium are CRMs that are difficult to extract and process, but can be captured from residual waste streams from zinc processing in Norway and Finland. Technology for extracting these elements exists, but is not implemented. If implemented, the stakeholders will face very different legislation whether an extraction plant is installed as a processing step in the existing hydrometallurgical plants – or if it is established as a stand-alone unit processing the jarosite zinc sludge already classified as a hazardous waste.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	low
Expected cost effectiveness of measure:	moderate

6.3 Measures for improved recycling of waste containing CRMs

Program that monitors progress towards specific recycling targets for critical elements.

CRMA contains specific recycling targets for individual CRMs, not only CRM as a group. A program that monitors annual progress towards these goals will be an important tool in evaluating the national CRM-strategies that is implemented to reach these targets. The national statistic that is required for this purpose will be more detailed than existing waste statistics.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	moderate

State guarantee for recycling facilities.

Compared to mines, recycling plants have increased risks when it comes to access to feedstock. While a mine can map its geological resources in detail and plan with a long-time horizon, recycling facilities are at the mercy of constant changes in what products are put on the market and what ends up in the waste. To increase recycling with more metals and ensure that the most important metals are also recycled, government minimum price guarantees should be considered, as is done in the agricultural sector with a target price for foodstuffs or in the energy market with contracts for difference.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	high

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

No technology currently exists for recycling of many CRMs and waste streams where they occur. This means that although such CRM-enriched waste streams can be collected, no facilities are able to process it to recover available CRMs. For this reason, there is a need for massive R&D efforts to develop necessary technological solutions for CRM-recovery that cannot be done today.

Many existing recycling technologies that are currently deployed in recovering CRMs operate with low recovery rates and only recover one or a few CRMs, while remaining CRMs in the feedstock is lost. One example of this is recycling of circuit boards where copper and gold is recycled while tens of other important CRMs including tantalum, gallium, germanium and PGMs are lost in the slag. R&D efforts should be considered for developing or improving the following recycling options:

- More effective recycling of minor CRMs from PCB and portable batteries.
- More recycling of shredder residue.
- Extracting copper, antimony and bismuth from ammunition and sediments from firing ranges.
- Extraction of phosphate from food waste, manure, sludge and bio residue from biogas production.
- Synthetic graphite production based on CCU.
- Recycling of baryte from offshore drilling fluids.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

Minimum requirements for recycling efficiency when delivering CRM-enriched waste to recycling.

If several recycling options exist, CRM-enriched waste should be delivered to facilities that guarantee the most efficient recovery of available CRMs. To achieve status as a preferred recycling option, necessary documentation should be required from the recycler that verify minimum industry standard recycling performance. This minimum recycling requirement standard should not be set either unrealistically high or unreasonably low but reflect realistic recycling performances.

Expected effect of this measure:	low
Expected financial costs of implementation:	low
Expected cost effectiveness of measure:	moderate

Mandatory reporting of recycled secondary CRM from recyclers.

Operators that recycle CRMs, should report actual recycling performance and the recovery rate of individual CRMs that are found in the processed feedstock to ensure optimal utilization of available waste streams for CRM-recycling.

Expected effect of this measure:	low
Expected financial costs of implementation:	low
Expected cost effectiveness of measure:	low

Incineration of selected waste streams in different W2E-plants that result in enhanced CRM-levels in ashes.

Ashes from incineration of waste contain all CRMs, some in sufficiently high concentrations that recovery may be an option. When mixed waste from many sources is incinerated, the ashes will generally contain lower CRM-concentrations than if CRM-enriched waste streams are incinerated separately. One way to obtain ashes with more favourable levels of CRM for recycling may be to dedicate selected W2E-plants for incineration of CRM-enriched waste streams like shredder residue. However, such a practice may present process challenges regarding incineration temperatures and flue gas cleaning.

Expected effect of this measure:	moderate
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

State investment fund that supports the establishment of new CRM recycling.

Building new Nordic CRM recycling capacity comes with considerable financial risk in today's market. This risk can be lowered by a state investment fund that provides partial capital for financing Nordic CRM-recycling projects.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

National CRM-stock pile program that buys secondary CRM-products at regulated prices.

Strategic stockpiling of CRMs in the Nordic can reduce short and intermediate supply risks and provide a more predictable market situation for Nordic recycling plants that provide secondary CRMs. Historically, stockpiling of critical resources was much more common, for example during the Cold War era. However, increasing market liberalism appears to have reduced the political will to maintain strategic raw material stocks. This is an attitude that should perhaps be reconsidered in today's global geopolitical climate.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

Requirements or incentives for the use of secondary CRM products and materials in public procurement schemes.

For public projects that consumes CRM-containing products or materials, requirements for choosing options based on secondary CRMs should be introduced in the procurement scheme. Alternatively, the procurement scheme should be updated to take recycled content into account as an award criterion.

Expected effect of this measure:	high
Expected financial costs of implementation:	moderate
Expected cost effectiveness of measure:	high

Consider the establishment of a joint Nordic alum shale CRM recycling plant.

Nordic alum shale could be turned from a problematic waste issue to a relevant regional resource. As alum shale already is inflicted with a substantial gate fee for its treatment, this provides a financial advantage compared to mining of conventional ores. Alum shale contains many CRMs, including REE and base metals, sometimes at concentrations that could prove to be the extractable. If a CRM-recycling plant for alum shale is established this should be followed by a Nordic ban or restrictions on landfilling of alum shale.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

Residues from zinc processing should be considered for CRM-recycling.

If proper extraction technologies for residues from zinc processing are implemented, it may be possible to extract both indium, germanium and gallium from these waste streams in volumes that may cover all Nordic needs. If the millions of tons of jarosite from earlier production is reprocessed as well – all European needs could be covered. The development of such a recycling process is expected to be costly and should receive financial support. A Nordic CRM recycling strategy for residues from zinc processing should consider a ban on todays practice where hazardous wastes without CRM value are blended with CRM-rich fractions. If a recycling process is established, use of jarosite as material for ceramic or glass production should also be restricted.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

EAF-dust should be considered for CRM-recycling.

When iron and steel is recycled, EAF-dust is created as a waste stream. EAF dust contains many CRMs at concentrations that may be recyclable, but so far EAF recycling operations have focused almost exclusively on the recovery of zinc. Technologies for recovery of additional elements have been developed but are so far not implemented on an industrial scale. If CRM recycling for EAF-dust becomes available landfilling and export to low quality recycling of EAF-dust with recoverable levels or CRMs should be banned.

Expected effect of this measure:	high
Expected financial costs of implementation:	high
Expected cost effectiveness of measure:	moderate

7. Preliminary conclusions and proposals for further work

Critical minerals are necessary for human life and our modern society. The minerals are also the foundation in the ongoing transformation of the economy based on fossil carbon to an economy based on metals. Independent access to these minerals through mining, recycling and global partnerships are necessary to keep Europe safe and secure. CRMA introduces important but challenging recycling goals for CRM. Increased recycling of CRMs is possible, but many barriers currently limit further development of value chains for secondary CRMs. This report summarises potential measures that may be instrumental for hitting the recycling targets presented by CRMA. Some measures are more or less locked in as requirements in CRMA. This includes setting up programs for mapping CRM waste streams with CRM recycling potential and implementing routines for statistical description of CRM-material streams.

Although some assumptions have been made in this report about waste streams that should be considered for CRM-recycling, a systematic mapping of waste streams with recoverable levels of CRM must be performed before any final assessment can be done about the potential for CRM-recycling from Nordic waste streams.

When a comprehensive description of the CRM-recycling potential is available, the next step will be to set up a system for collection and pretreatment of relevant waste streams so they can be efficiently used as feedstock for a recycling operation. To ensure cost efficiency, collection of CRM-waste should if possible be integrated with existing waste collection schemes to ensure rational and cost-effective collection operations. Many waste streams need pretreatment before they can be recycled. Most often this involves sorting that separate CRM-materials from other materials in the waste stream that do not contain recoverable CRMs. A barrier to efficient sorting of many waste streams is lack of available technology for advanced automatic sorting operations. Nordic countries should consider R&D-projects that can provide better technological solutions in this sector.

EPR-schemes that handle waste streams with recoverable CRMs can ensure better recycling of many CRMs than what happens today, and the framework conditions for these EPR-schemes should be updated accordingly. These EPR-schemes include WEEE, scrapped vehicles and tyres. New EPR-schemes should also be considered for discarded products and materials with recoverable CRMs that form waste streams that fall outside of existing EPR-mandates.

Both technological and economic barriers limit recycling options for CRMs. For many CRMs no recycling technology is currently available. It is therefore of crucial importance that increased efforts are put into the development of new and improved recycling technologies for many CRMs. Many recycling processes for metallic CRMs only recycle a limited number of metals which often leads to significant loss of niche CRMs in both slag and as pollutants in secondary products. Efforts should be made to improve the efficiency of these processes and to increase the number of CRMs that are recovered.

The cost efficiency of the value chains for secondary CRMs must also be addressed, and it is hard to imagine necessary profitability without better economic support systems for Nordic industries that are comparable to the operational conditions in for similar industries in China.

The Nordic Countries could benefit from a common approach to improved recycling of CRMs, as the Nordic countries are rich in mineral resources and are already active in extraction and processing of critical raw materials. This expertise and technology base can be further developed in cooperation with research institutions and entrepreneurs.

This report shows that there are huge volumes of critical raw materials that are lost as waste every year. For many of these raw materials recovery routes exists. For some CRMs the 25% recovery will be very difficult to reach, but for others – much higher recovery rates can be achieved.

In the waste fractions we have described in this report, there are almost 1 million ton of CRM[27] that is currently lost annually.

27. Excluding several millions of tons of the bulk materials silicon, magnesium, aluminium and titanium.

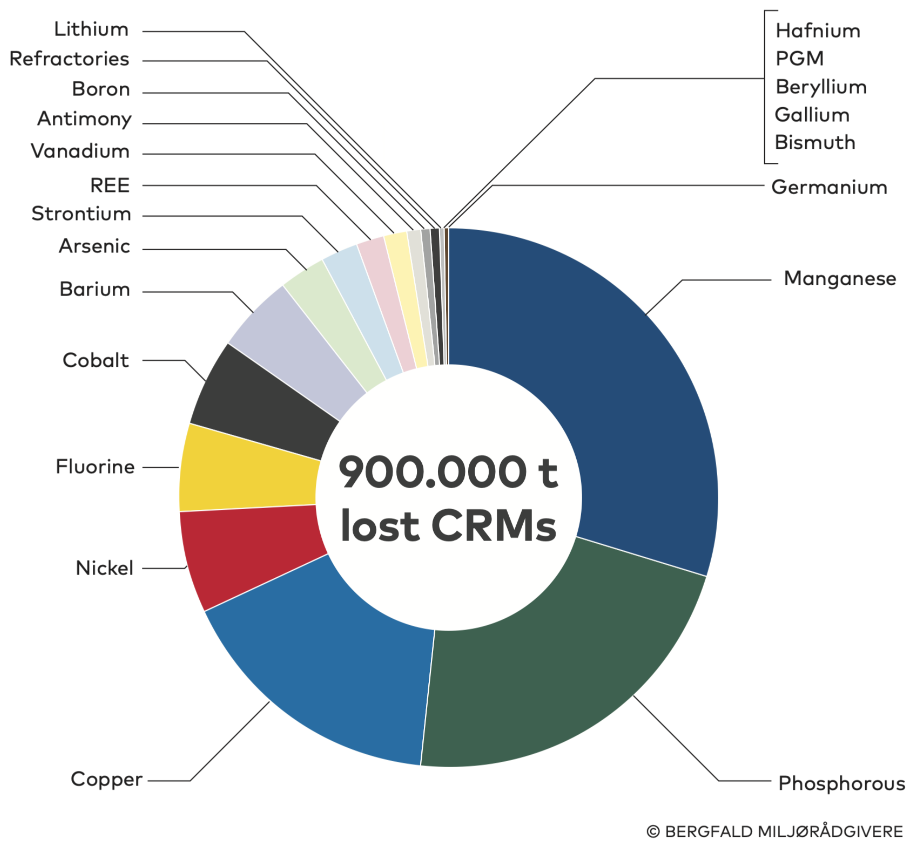


Figure 7.1 New industries can be built, and waste landfills avoided as CRMA requirement are implemented.
Source and illustration: Bergfald Miljørådgivere.

It seems obvious that these waste streams can provide a lot of benefits for the Nordic societies if recovered and used for new products and materials. Benefits such as increased circularity, reduced landfilling, stable and sustainable workplaces and secure access to raw materials for the downstream processing industries.

As already described, increased recovery of CRMs will require removal of barriers and introduction of incentives. These barriers can be immature technology, regulatory restrictions, purity requirements, industrial standards, financial incapacity, lack of interest, small and dissipated amounts, immature markets, open and unprotected markets etc. Almost every barrier described in this report can be interpreted as an economic obstacle and can therefore be reduced or eliminated through better financing solutions.

Recycling of CRMs are part of the fundamental shift from a linear to a circular economy and should be considered as one of the most important parts of this change. The conversion of our industrial infrastructure to support closed technical loops for important raw materials will require large changes in the waste legislation, the end-of-waste-criteria as well as how materials are recycled to avoid downcycling and locking in CRMs in structures that cannot be recycled.

Markets for many of the CRMs are small in terms of volume and money, even if they are of strategic importance to society. The market is therefore limited, and not all countries will have recycling plants. Those that are established, will need initial financial aid and a protective legal framework.

7.1 Suggestions for further work

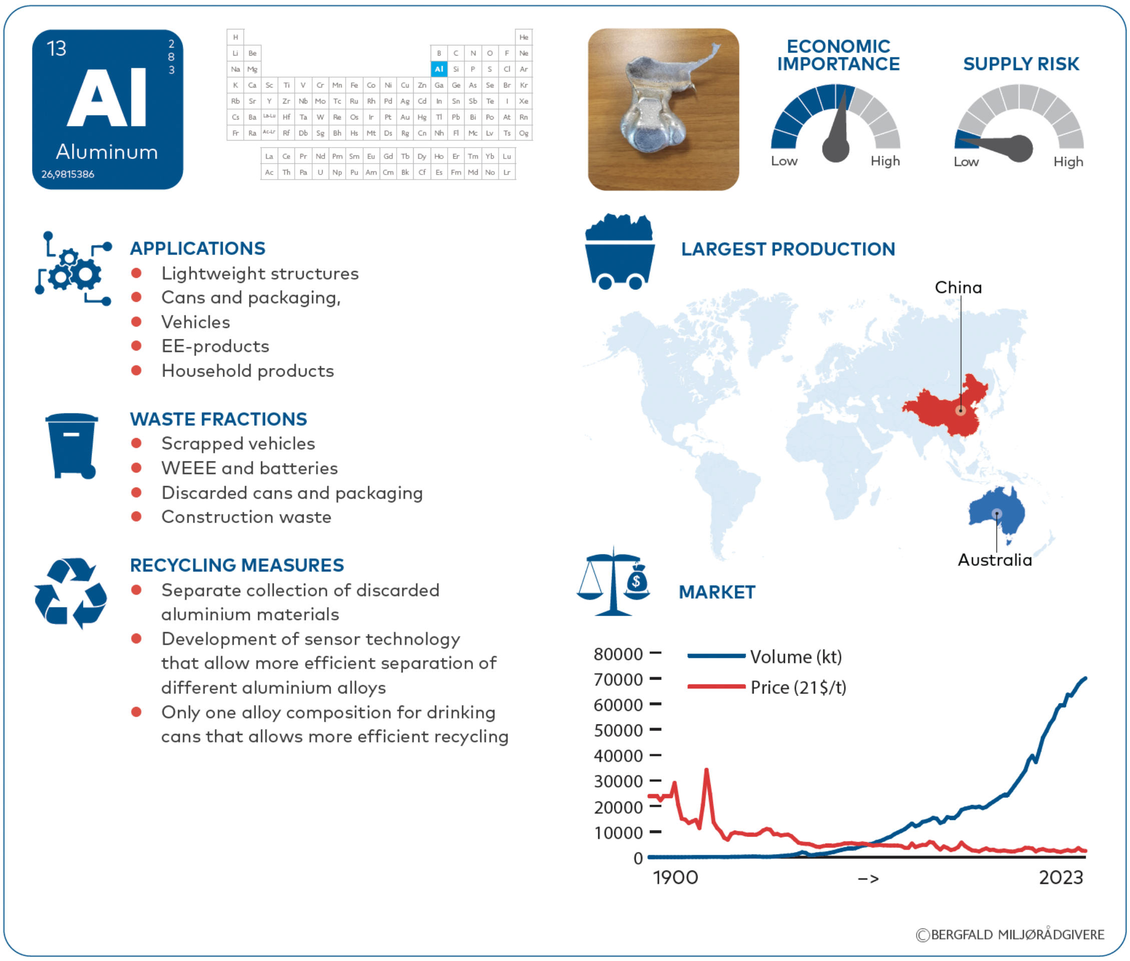
CRMs have different sources, follow different value chains and end up in different waste streams. As such, there are no magic set of incentives or regulations that will easily solve all issues for all CRMs. However, there are still some issues of broad interest that deserves a closer look:

- **The low hanging fruits.** There are some waste categories which easily and rather inexpensively could be recovered with a minimum of regulatory and financial support. Examples could be the P/REE-flotation-sludges in Sweden, REE in phosphogypsum in Finland, electronics from scrapped cars, metal content of shredder fines etc. These are large volumes of waste with high CRM-content without good reasons for already being in production. A few niche fractions such as gallium-containing sludges and dust from zinc and aluminium refining is also too rich to ignore. A goal for work in 2024 should be to find what bottlenecks there are for recovery from these fractions, if any – and how to quickly remove the bottlenecks.
- **The dominance of gold.** WEEE contain all the CRMs in addition to several other elements of importance and value. Currently, WEEE is recycled based on overall weight and value. It could be argued that the most important contribution provided by the Critical Raw Materials Act is the specific recycling requirement for each of the CRM elements. For WEEE components, such as PCBs, this will probably not be sufficient to secure recovery. As the value of gold will dominate over the value of CRMs, the PCBs will go directly to gold recovery in industries where most of the CRMs are lost. To counter that, a work package should be defined to develop a mandate of 25% extraction/preprocessing of PCBs before gold smelting.
- **How to protect the critical**. It is assumed in the industry policies of the Nordic countries that all production plants should be operating on market economy terms. However, our current situation has shown that European CRM-industry needs equivalent protection mechanisms to what is given in other countries to survive. Indeed, any and all CRM recycling plants will be small and vulnerable to market manipulation and will need either direct support or market protection to survive. Without such support or protection, it might be difficult for the Nordic countries to attract private and industrial investors. Indeed, a closer study should be made to see how Japan, USA and other market economies organized legislation to develop and protect their CRM industries.

- **From toxic to critical.** Many waste fractions contain both toxic and hazardous elements and critical raw materials. Indeed, there will be significant conflict between legislation designed to avoid dissipation and release of toxic elements and the new legislation designed to increase recovery of critical elements. There is a need for a closer look into how these conflicts can be avoided or mitigated, and how recovery mandates can be developed and implemented without risking increased problems with hazardous wastes.
- **The concrete problem.** Increasingly, industrial waste and slag are used to produce concrete and concrete precursors. There are good reasons why this is so, from both a resource and energy/climate perspective. However, when slag and waste are included in the concrete, it will never be possible to recover again. Hence, new guides or policies need to be developed to sort out when it is better to use slags for concrete and when it needs to be processed to recover CRMs.
- **The dissipation issue**. Most major metals end up as alloys when in use. Alloyed metals are tailormade for its application, but that creates a problem when mixed metals are recycled. In both steel and aluminium, there are problems with levels of contaminants increasing, efficiently both creating a barrier for increased circularity as well as a permanent loss of certain minor CRM elements. A work package should be defined to see if current recycling practice with smashing of spent equipment in hammer mills is suitable for a circular economy or if more advanced remanufacturing is needed.

Appendix 1 Critical raw materials for EU

Aluminium/bauxite



Applications and market situation

Bauxite is today the only raw material for production of aluminium and is listed as a critical raw material by all the major powers including USA, EU, China and Russia. This situation exists even though bauxite is found in huge quantities on all continents, is easily available and easy to process. Listing of bauxite as a critical raw material is also despite the fact that aluminium can also be produced from minerals other than bauxite.

The global production of primary aluminium is around 65 million tons. Only 21% of discarded aluminium materials is recovered. To produce one ton of aluminium, around 4 tons of bauxite is needed which creates approximately 3 tons of sludge. Production of primary aluminium also require large amounts of power, approx. 16 kWh/kg. In comparison recycling of aluminium require approximately 1 kWh/kg, which means that recycling of aluminium significantly minimize waste generation and energy consumption compared to primary production. The sludge from primary production of aluminium often contains recyclable amounts of other CRMs like gallium, indium, vanadium, selenium and rare earths. Recycling options for CRMs other than aluminium from waste from the aluminium industry is discussed in appendix 3.

Waste streams and systems for recycling

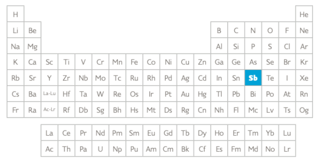
Despite strong environmental arguments and favorable economic conditions for aluminium recycling, little progress in recycling rates have been accomplished in later years. This should be seen in light of the strong growth in China, which has led to a sharp increase in primary production that has not yet been discarded as waste. Regardless, aluminium recycling rates both could and should easily have been higher, indicating that there may be a need for stronger political and economic incentives for recycling.

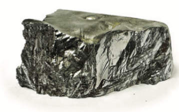
Many aluminium materials are alloys, and often contain other CRM-components such as manganese, zirconium or cerium. New technology in optical and laser reflection sorting is under development and implementation. This can make it possible to sort different aluminium components according to alloy, thereby achieving higher quality recycling.

Recycling of drinking cans is an important recycling option for aluminium. However, several aluminium alloys are used in cans and when these are melted together suboptimal mixing of metal components is created and collected as an output leading to loss of CRMs in secondary aluminium and a need for additional primary aluminium and CRM additives to achieve necessary alloy quality.

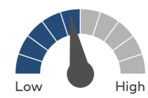
Antimony

51
2 8 18 18 5
Sb
Antimony
121,76

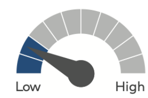




ECONOMIC IMPORTANCE



SUPPLY RISK



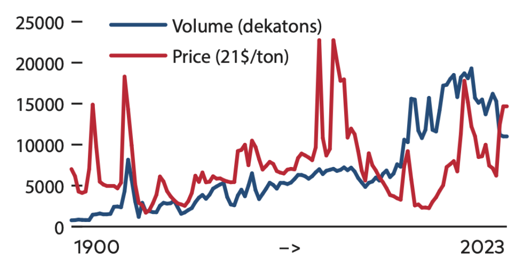
APPLICATIONS
- Alloys
- Flame retardants
- Lead-acid batteries
- Ammunition

WASTE FRACTIONS
- Lead and tin alloys
- Lead batteries
- Ammunition residues
- Incineration ash

RECYCLING MEASURES
- Increase recycling rate of antimony from lead recycling
- Extracting of antimony from ammunition and sediments from firing ranges
- Extraction of antimony from W2E incineration ash.

LARGEST PRODUCTION

MARKET



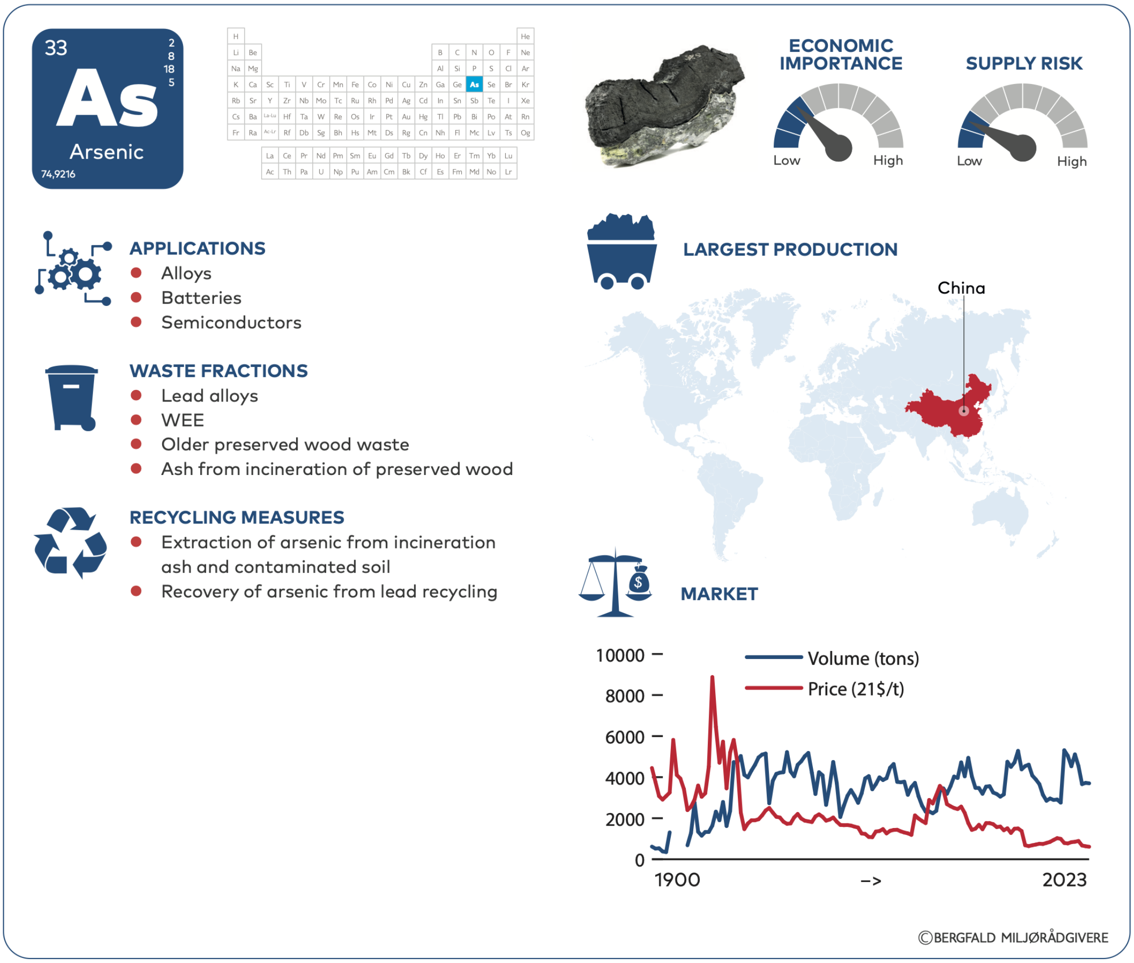
Applications and market situation

Antimony is a metallic element that has its main use as a flame retardant and additive in metal alloys, especially in lead and tin. Antimony-lead alloys are commonly used in lead batteries and lead-containing ammunition, and sometimes also in semiconductors, machine parts and tools. Antimony is also used as an additive in PVC plastic, paint and glass and ceramic materials, solder, and cable protection and as a catalyst to produce PET plastic. Antimony is harmful to health and both inhalation of dust and skin contact should be avoided. For many applications of antimony, substitution options do exist but sometimes with diminished function and at higher costs. Inorganic alternatives to antimony as flame retardants include hydroxides of aluminium and magnesium and various phosphate compounds. For ammunition there are lead-free alternatives that also eliminates the need for antimony. Antimony is a relatively rare element and occurs in the Earth's crust in low concentrations of around 1 ppm. The most common antimony-containing mineral is the sulfide mineral stibnite (Sb2S3). The total world production of antimony is around 100,000 tons. Production of antimony metal occurs by roasting ore and reduction with carbon or direct reduction using iron. China has for many years been the largest producer of antimony. However, this production is stagnating due to increasingly strict environmental requirements, and there is a growing concern that additional Chinese production will disappear in the coming years.

Waste streams and systems for recycling

The main proportion of secondary antimony is produced as a by-product of secondary lead production, and discarded lead batteries are an important feedstock for this recycling process. European recycling rate of antimony is estimated to be 28%. Other potential feedstocks for antimony recycling processes may be ammunition remnants, spent catalysts from production of PET-plastic and ash from waste incineration. Although there is to our knowledge no direct recycling of antimony in the Nordics, it may be recovered as a byproduct from the Boliden Bergsøe plant in Landskrona and Sala Bly.

Arsenic



Applications and market situation

Arsenic is a toxic chemical element with atomic number 33. Arsenic is the 53rd most abundant chemical element in Earth's crust and is typically found in minerals with the formula XAsS and XAs_2 where X may be iron, cobalt or nickel. China is the main producer of arsenic with around 42% share of the global production.

Main applications of arsenic are as components in alloys, batteries and semiconductors. Most arsenic is used in alloys of lead, and as semiconductor arsenic is found in electronic products such as gallium arsenide. Historically arsenic was used as biocide including wood preservation, but most biocide use of arsenic has been banned. Being very toxic, soil and sediments contaminated with arsenic will sometimes be cleaned by remediation processes where arsenic is removed.

Waste streams and systems for recycling

No significant recycling of arsenic seems to occur neither in the Nordics nor the rest of the world. There are however dedicated incineration plants for CCA-waste, which brings forth a waste with high arsenic content that may serve as feedstock for arsenic recycling. Compared to many other CRMs, recycling of arsenic seems less urgent.

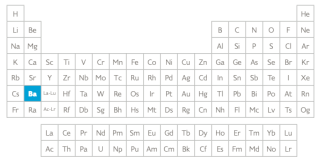
Baryte

56 | 2 8 18 18 8 2

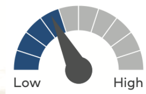
Ba

Barium

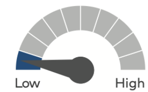
137,327



ECONOMIC IMPORTANCE



SUPPLY RISK



APPLICATIONS

- Drilling mud,
- Filler
- Barium chemicals

WASTE FRACTIONS

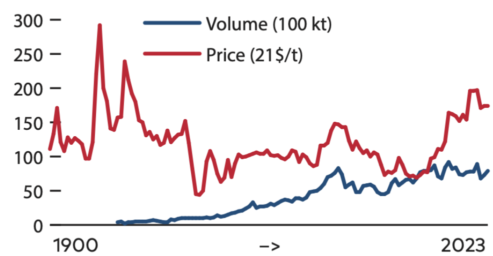
- Discarded drilling fluids

RECYCLING MEASURES

- Separate collection of drilling fluids containing baryte
- Monocell landfilling of baryte containing drillingfluids and cuttings
- Mapping historic locations of baryte rich offshore waste for future recycling operations
- Developing recycling process for baryte from drilling fluids

LARGEST PRODUCTION

MARKET



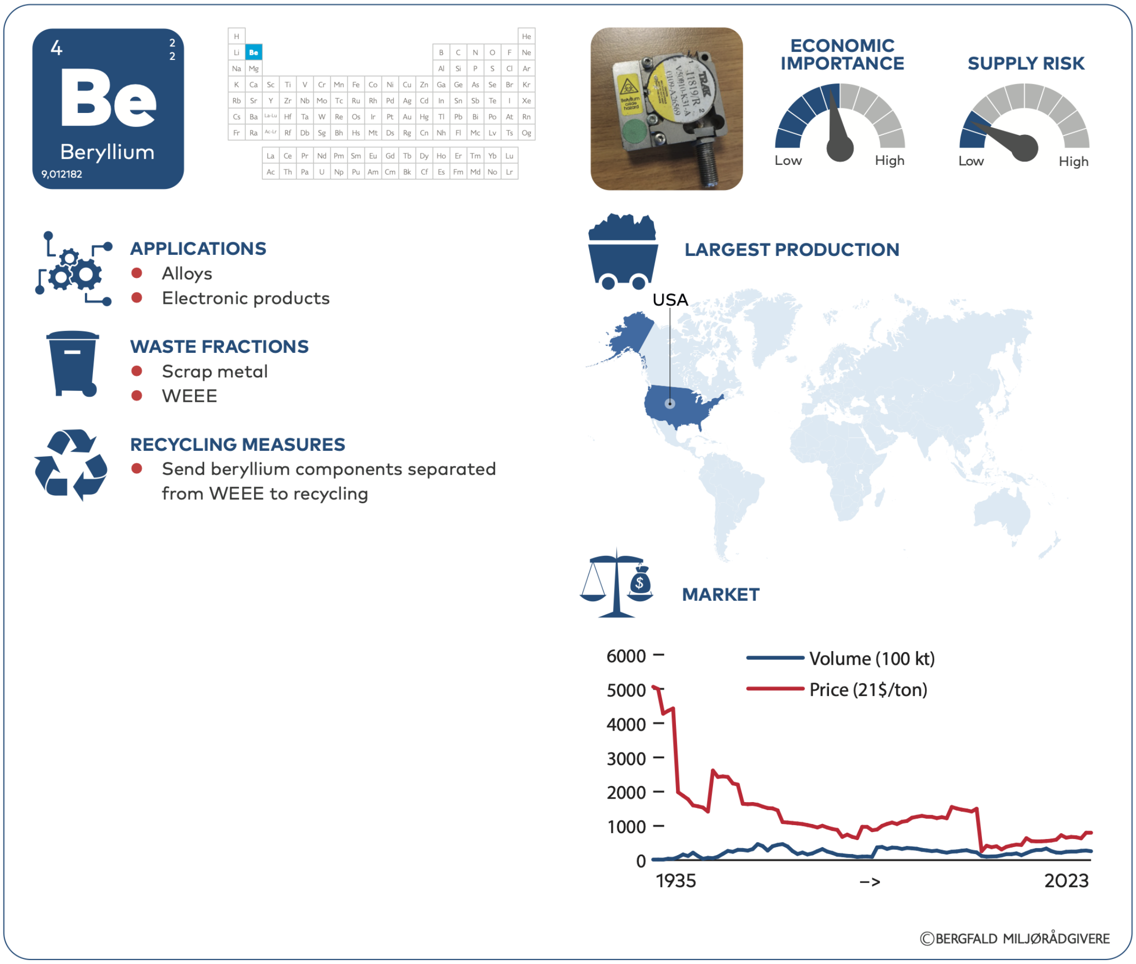
Applications and market situation

Baryte is a mineral with the chemical composition of $BaSO_4$. The global production of baryte is estimated to be around 8,4 million metric tons (2019) with India and China as the biggest producer. The main application of baryte is as weight material in drilling mud, filler and raw material for production of barium chemicals.

Waste streams and systems for recycling

No significant recycling of baryte seems to occur neither in the Nordics nor the rest of the world. Baryte could however be extracted from spent drilling fluids if necessary. Compared to many other CRMs, recycling of baryte seems less urgent.

Beryllium



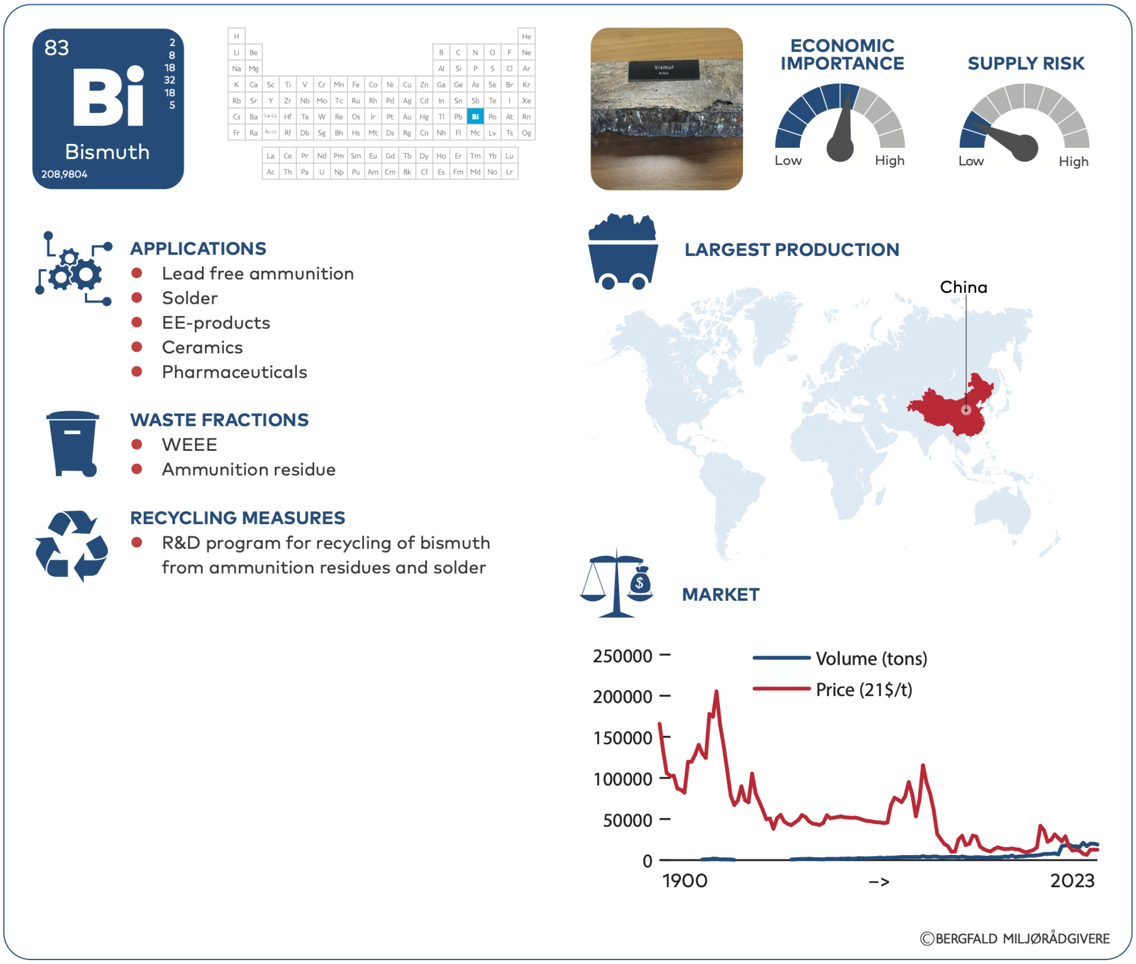
Application and market situation

Although beryllium is extremely toxic, the chemical element also has important technical applications especially in advanced alloys. Historically, beryllium was primarily used in weapons systems and space travel, but in later years beryllium has also found increasing civil applications, most importantly in electronic products and alloys. Global annual production of primary beryllium is small and around 300 tons.

Waste streams and systems for recycling

Recycling of beryllium do exist, but there is no recycling capacity for beryllium or beryllium-containing alloys in the Nordic countries, neither in EU/EEA. Beryllium-containing components during WEEE dismantling are routinely separated due to health hazard, but handled as hazardous waste.

Bismuth



Applications and market situation

Bismuth is a brittle, high-density metal that has similar properties as lead, but is less toxic. For this reason, bismuth is sometimes used as a substitute for lead. Global production of bismuth is around 20,000 tons, and the main producer is China. Applications of bismuth include use as lead free ammunition, alloying addition in solder and EEE-products, ceramics and pharmaceuticals.

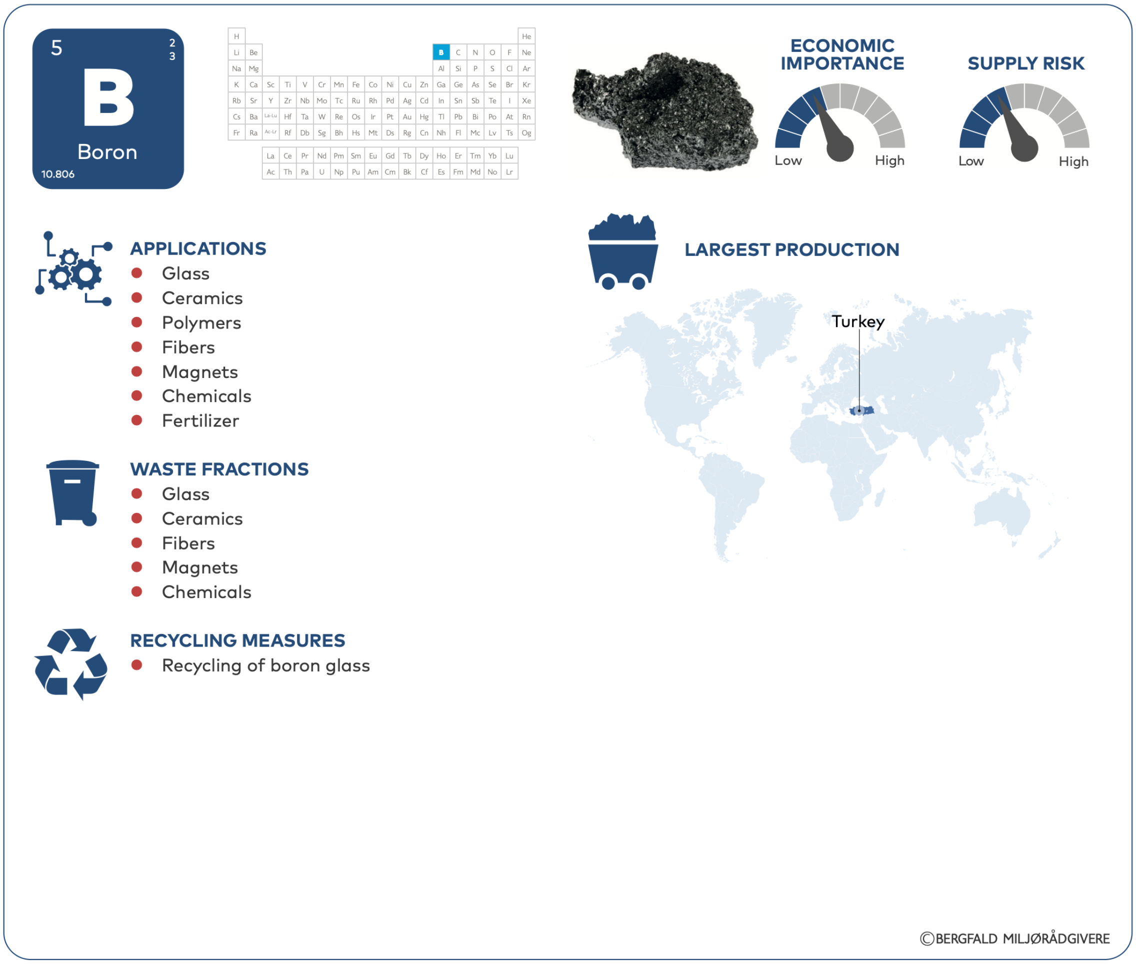
Bismuth is mainly extracted as a by-product of lead, and for this reason, reduction in the consumption of lead will also make bismuth less available although bismuth is also found in other industrial material streams, for example from copper and tin production.

Waste streams and systems for recycling

Most industrial users of lead solder have over time worked to minimize the consumption, and often switched to alloys with less lead. Use of solder also causes significant formation of scrap and dross in later recycling processes. During the work with this report no Nordic bismuth recycling capacity was identified, although components that contain bismuth are recycled for other CRMs. For example, recycling of circuit boards recover copper and silver, while tin and bismuth end up in the slag.

Low concentrations and interactions with other chemical elements make bismuth recycling from WEEE very challenging and may not be a realistic technical option for some time.

Boron



Applications and market situation

Boron is a chemical element with atomic number 5 and constitutes about 0.001% of Earth's crust by weight. Due to its water solubility many boron minerals are found as evaporites, including borax and kernite. The largest known deposits are in Turkey, and Turkey is also the global largest producer of boron minerals, making European industry heavily reliant on Turkish imports.

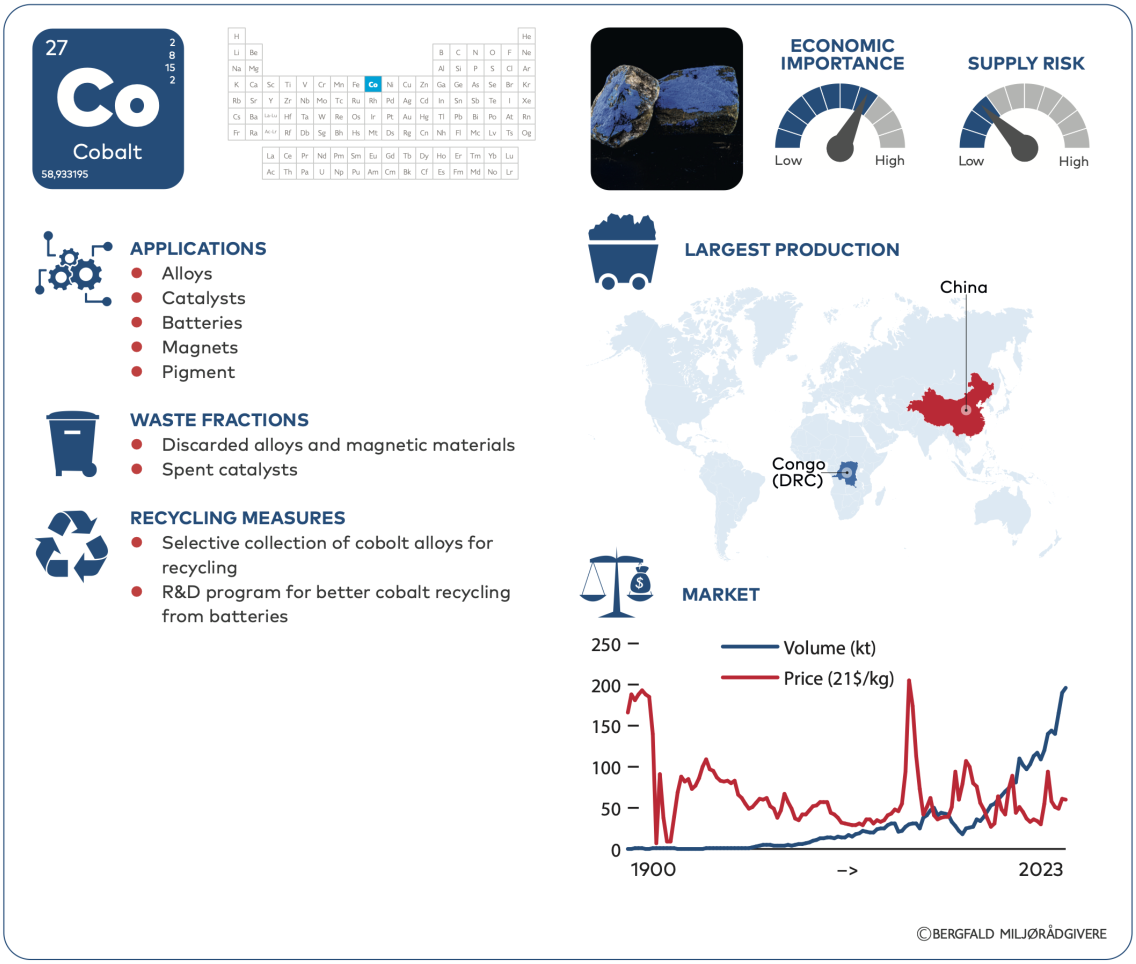
Important applications include additives in glass, ceramics and polymers. Boron compounds are also used as bleach and other chemical purposes, and small amounts are also used in electronic products. Although only very small amounts are needed, boron is also an essential plant nutrient.

Global consumption of boron compounds was about 5 million tons in 2021.

Waste streams and systems for recycling

Boron recycling is very low, estimated at around 1%, and no significant recycling capacity of boron has been identified in the Nordics or EU/EEA during the work with this report. For most applications of boron it is difficult to see easily available recycling opportunities.

Cobalt



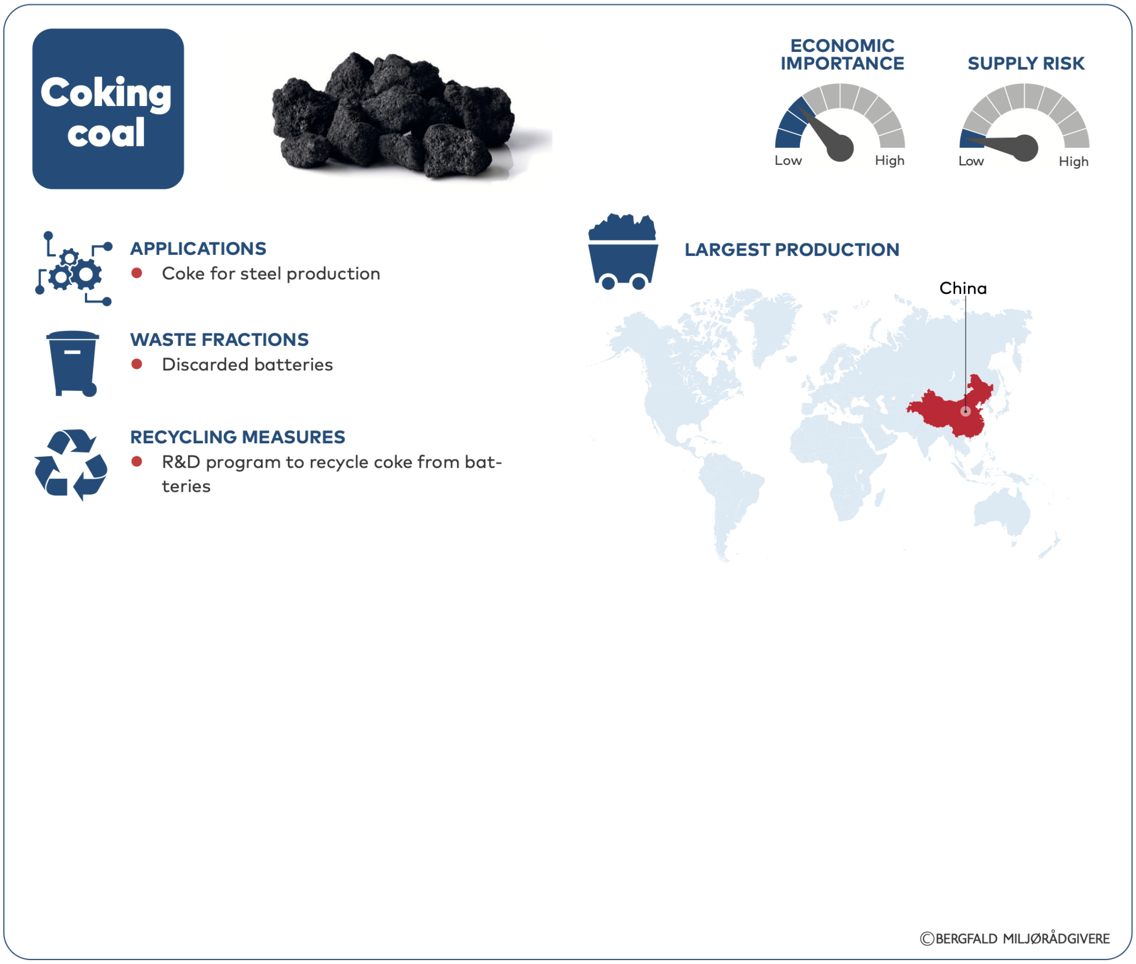
Applications and market situation

Cobalt is a silvery metal with atomic number 27 and comprises 0.0029% of the Earth's crust. Today, some cobalt is produced specifically from one of a number of metallic ores, such as cobaltite (CoAsS), but more often as a by-product of copper and nickel mining. The Copperbelt in the Democratic Republic of the Congo (DRC) and Zambia yields most of the global cobalt production. World production in 2021 was 166,000 tons. Cobalt is primarily used in lithium-ion batteries, and in the manufacture of magnetic, wear-resistant and high-strength alloys. Cobalt is also used in the petroleum industry as a catalyst for removing sulfur from crude oil and as a pigment. Cobalt is also the active centre of a group of coenzymes called cobalamins.

Waste streams and systems for recycling

Cobalt is recyclable, and the recycling rate is estimated to be 22%. The Nordic recycling capacity of cobalt is good as there are several processing plants available if cobalt in the future is recovered from wastes. These plants include the Nikkelverk plant in Norway and the Boliden plants in Sweden and Finland. From batteries, the LIB-recycling plants are taking out black mass containing cobalt that in the future will be recycled in these refineries.

Coking Coal



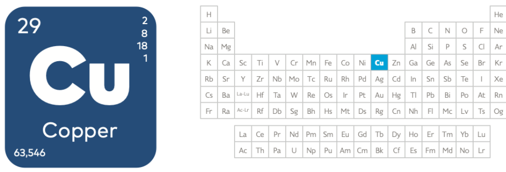
Applications and market situation

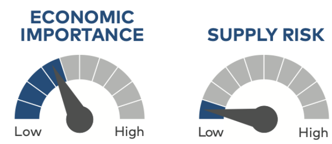
Coal is a carbon-based mineral that comes in many qualities. Coking coal also referred to as metallurgical coal and is grade of coal that can be used for production of high-quality coke. Coke is used in the blast furnace process for primary steelmaking and other industrial processes. Minor applications also include carbon fibres and battery electrodes. China, Australia and Russia are large producers of coking coal. The global production of coking coal in 2021 was about 1 billion tonns.

Waste streams and systems for recycling

Coke used for either metallurgical purposes or fuel is chemically converted and cannot be recycled. Today there are no significant recycling of coking coal neither in the Nordics nor the rest of the world. Although coke from batteries theoretically can be recycled it is hard to imagine a recycling process for metallurgical coke.

Copper





APPLICATIONS

- EE-products and electric infrastructure
- Construction material and water pipes
- Biocide

WASTE FRACTIONS

- WEE and cables
- Construction waste and decomissioned infrastructure

RECYCLING MEASURES

- Better collection and sorting of copper waste
- Better protection of WEEE from theft and looting
- R&D program for more recycling of shredder residue
- R&D program for extracting copper, antimony and bismuth from ammunition and sediments from firing ranges

Applications and market situation

Copper is a malleable and ductile metal with very high thermal and electrical conductivity. It comprises 50 ppm of Earth's crust making it the 26th most abundant element. Copper was the first metal used by mankind, more than 8000 years ago. It has always been valuable and corrodes little, with the result that about 80% of all copper ever mined is still in use. The main global producers of copper are Chile, Peru and China.

Due to its many favourable properties, it has many applications most importantly as an electric conductor in electrical wires and cables. Copper also has many other important electronic applications among other things in electric motors and dynamos. Copper and copper alloys are also in widespread use as construction material in consumer products and building structures, and as a biocide in various contexts. The global consumption of copper in 2021 was about 25 million tons.

Waste streams and systems for recycling

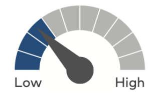
Recycling of copper has a long history and has resulted in an advanced and well-developed value chain for production of secondary copper. The European recycling rate for copper is about 30%, and there is a huge capacity in copper recycling in the Nordics. The Boliden plant in Skelleftå is by far the most important. Indeed, most of copper containing WEEE scrap is currently sent there for recycling. There are also other possibilities for recycling, both in the Nikkelverk plant in Norway and the Boliden plant in Harjavalta. A further increase in copper recycling therefore relies on better collection and sorting of copper containing waste more than further development of recycling processes. The existing value chains have through its long operating history had time to develop solid technical and industrial capacity for further tonnages and handling of off-spec material with increased recycling efficiency.

In addition to copper that can be recycled from discarded products, huge amounts of copper are available in the form of buried cables, installed and disconnected power grids in buildings etc. During remediation of copper-rich infrastructure, it is important to have good routines and systems for handling demolition waste that effectively picks out copper-containing components and materials.

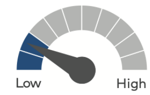
Feldspar

Feld-spar

ECONOMIC IMPORTANCE



SUPPLY RISK



APPLICATIONS
- Glass and ceramic products
- Fillers in paints, plastics and rubber

WASTE FRACTIONS
- Glass

RECYCLING MEASURES
- Increase separate collection of additional glass waste
- Increase Nordic glass recycling capacities

LARGEST PRODUCTION

Applications and market situation

Feldspar is not a chemical element, but a group of minerals that are quite abundant. As this mineral group make up about half of the Earth's crust[28] it may seem counter-intuitive that it is considered so scarce that it has made it on to EUs list of critical raw materials.

Feldspar minerals have a similar chemical structure and composition that can be described by the formula $X(AlSi)_4O_8$ where X may be either K, Na, Ca, Ba, Rb, Sr or Fe. Common feldspars include orthoclase ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$).

Feldspar minerals have many applications including being used as raw material for a wide variety of glass and ceramic products. Feldspar is also commonly used as fillers in paints, plastics and rubber. Several popular gemstones are feldspar minerals, including moonstone, sunstone, labradorite, amazonite and spectrolite.[29]

28. https://geology.com/minerals/feldspar.shtml
29. https://geology.com/minerals/feldspar.shtml

Global production of feldspar has been estimated to be around 26 million tons (2020). Turkey (7,6 Mtons) and Italy (4 Mtons) are large European producers of feldspar.[30]

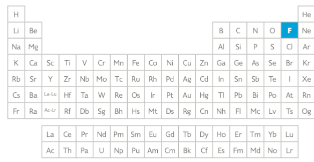
Waste streams and options for recycling

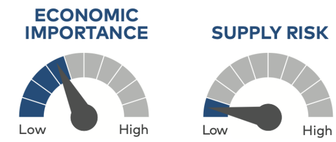
Recycling options for feldspar materials do exist, and European recycling rate for feldspar was estimated at 10%.[31] Feldspar in glass can be remelted into new products and particular waste streams of feldspar may be recovered and upgraded to feedstock quality.[32] Recycling of feldspar used as filler seems more difficult. Considering the relative abundance and geological availability of feldspar compared to other CRMs building increased feldspar recycling capacity should probably not be given the highest priority when Nordic CRM-recycling strategies are formulated.

30. Feldspar And Nepheline Syenite. U.S. Geological Survey, Mineral Commodity Summaries, January 2020
31. Report on Critical Raw Materials and the Circular Economy, European Commission, 2018
32. Scalable recycling of feldspar slime into high-quality concentrates by removal of coloured minerals using the combined beneficiation processes, Junxiong Zhan et al, Separation and Purification Technology, 2023

Fluorspar

9
F
Fluorine
18,9984032





APPLICATIONS

- Industrial chemicals
- Organic chemicals
- Pharmaceuticals
- Nonstick coating
- Gore Tex textiles
- Batteries

WASTE FRACTIONS

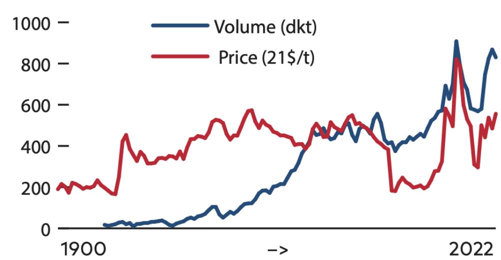
- Fluoridic waste from production of primary aluminium
- Hydrogenfluoride and fluoridic chemicals from industry

RECYCLING MEASURES

- Selective collection of recyclable fluorine waste from industry
- Establishment of fluoride recycling at Fluorsid Noralf in Odda

LARGEST PRODUCTION

MARKET



Applications and market situation

Fluorspar or fluorite is a fluorine mineral with the chemical formula CaF_2. Fluorspar is both used directly and processed into other fluoride compounds and elemental fluorine. The strong electronegativity of fluorine gives both organic and inorganic fluorine compounds important properties. Fluorine has many applications that include metal production, industrial extraction processes, textiles and nonstick coating, batteries and pharmaceuticals. Fluorine is also used in small amounts in many high-tech electronic applications.

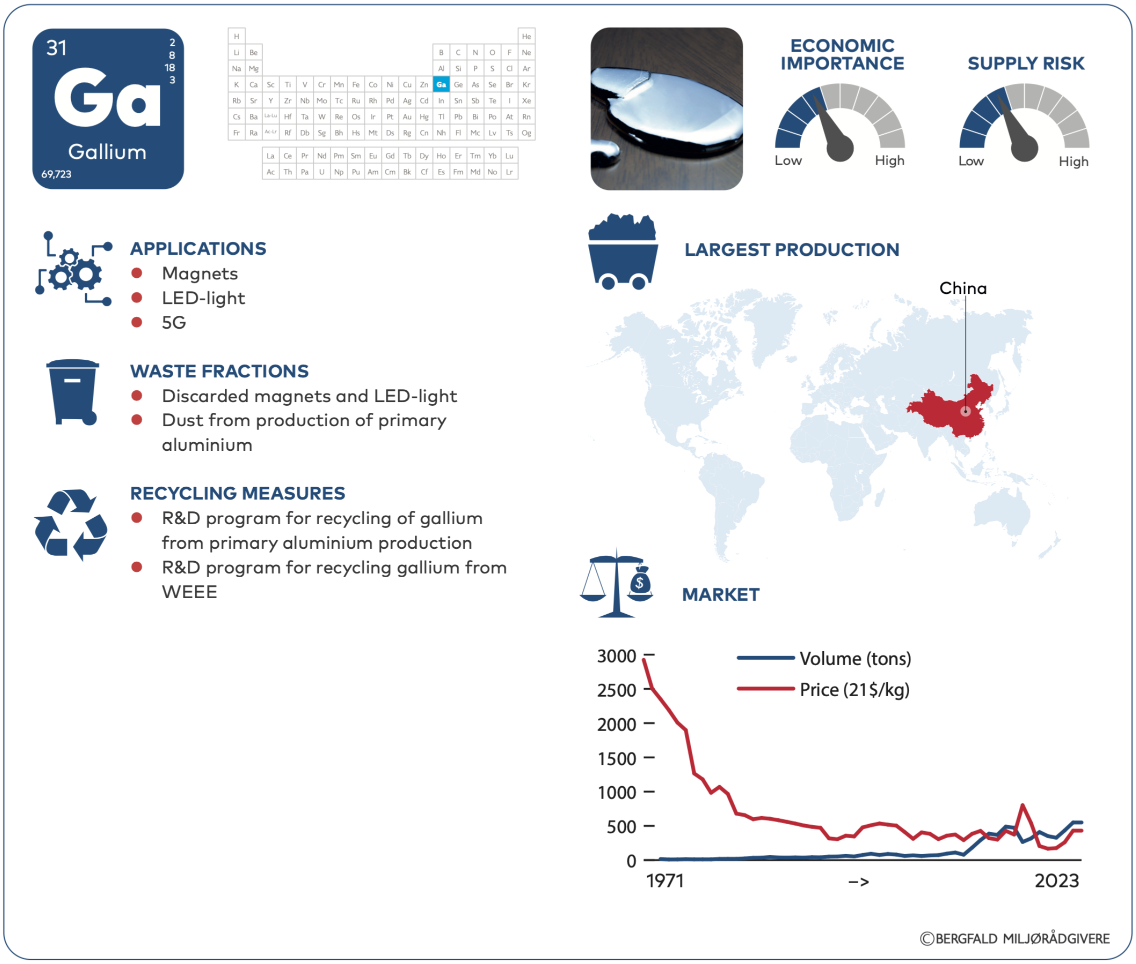
Fluorine is relatively available in the Earth's crust and ranks 13 as the most common element. Fluorine is supplied both from dedicated fluorspar mines and as a by-product from phosphoric acid production. The main global producers of fluorspar are China and Mexico. The global production of fluorspar in 2021 was about 8,4 million tons.

Waste streams and systems for recycling

Hydrogen fluoride (HF) and other fluorine chemicals are consumed in some production processes and end up as waste materials or sludge containing HF and CaF2 that can sometimes be recycled. Large amounts of recoverable fluorine are also used in the production of primary aluminium. Another recycling option is the hexafluorophosphate in the electrolyte in some lithium batteries. It is doubtful if this electrolyte can be reused directly due to chemical degradation. Chemical recycling could be possible, however. Actual recycling of fluorine is quite rare. The recycling rate of fluorine is about 1%, and no significant Nordic recycling operations for fluorine have been identified during the work with this report. There is however a Norwegian facility that could easily be adapted to recycling of fluorine waste. This facility is operated by Fluorsid Noralf and located in Odda where it currently produces aluminium fluoride based on Moroccan fluorspar.

As fluoridic waste is often both toxic and corrosive, comprehensive environmental and safety measures are necessary to ensure secure treatment. This combined with low prices makes profitable fluorine recycling challenging.

Gallium



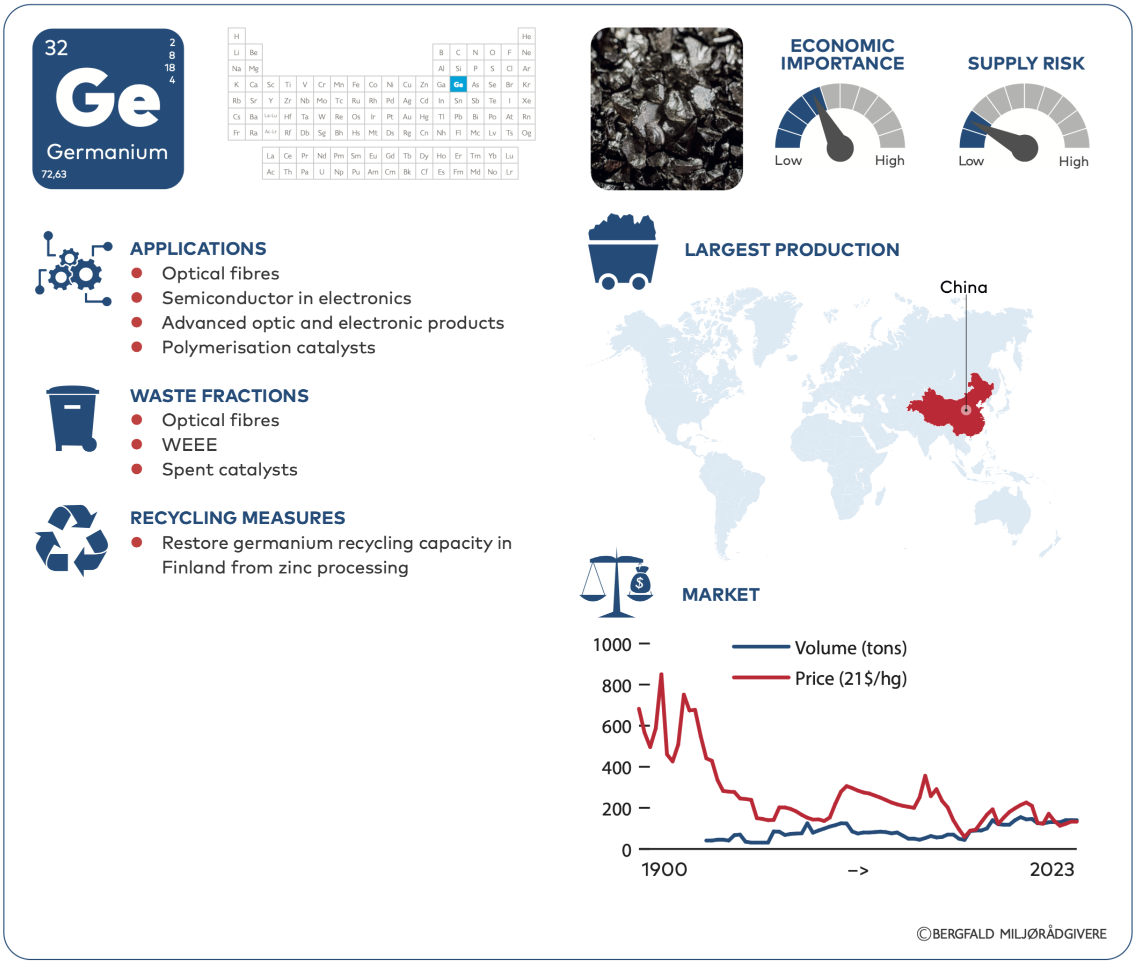
Applications and market situation

Gallium is a soft silvery semi-metal with atomic number 31 and special properties. It is ranked as the 35th most abundant element in the Earth's crust and is mainly extracted as a byproduct from zinc- and aluminium ore. Due to its unique properties gallium has been an important component in the electronics industry since infancy, and today plays a key role in two critical sectors. Firstly, gallium is the basis for almost all lighting as it is the main chemical component of LEDs, either as gallium nitride, gallium arsenide or other compounds, and is often mixed with either rare earth metals or transition metals in addition to adjust the wavelength of the light. Of all the elements, gallium has the best ability to convert electricity to light photons, which explains its dominant role in lighting products. In the last couple of years, a new market has emerged for gallium in neodymium magnets. Neodymium provides very good magnets, but the metal is brittle and cracks easily especially with rapid temperature fluctuations. There are many metals that can be added to the magnetic alloy to make the magnets more physically stable, but most of these will weaken the magnetic field or have other negative side effects. A few parts per thousand of gallium in the neodymium however leads to significantly more stable magnets without significantly affecting the magnetic strength. Despite these important applications the market for gallium not large, only about 430 tons in 2021. China is by far the largest producer of gallium.

Waste streams and systems for recycling

The main waste stream for gallium is WEEE, and both discarded LEDs and magnets represent sub streams that could potentially be recycled. There is practically no recycling of gallium in the world today from consumer waste. Hydro's seven Norwegian primary aluminium plants and the two plants of Alcoa represents one of the world's largest aluminium fleets. These plants consume 5 million annually tons of bauxite as refined aluminium oxide, with a high content of gallium. In the production process much of the gallium evaporates, and then condenses as part of the electrostatic precipitator dust. Two of the Norwegian aluminium plants deliver dust with about 2000 ppm gallium, while the other five have a dust with about 300 ppm. It may also be possible recycle gallium through separation of a gallium concentrate from the LED through grinding down and selective electrostatic separation.

Germanium



Applications and market situation

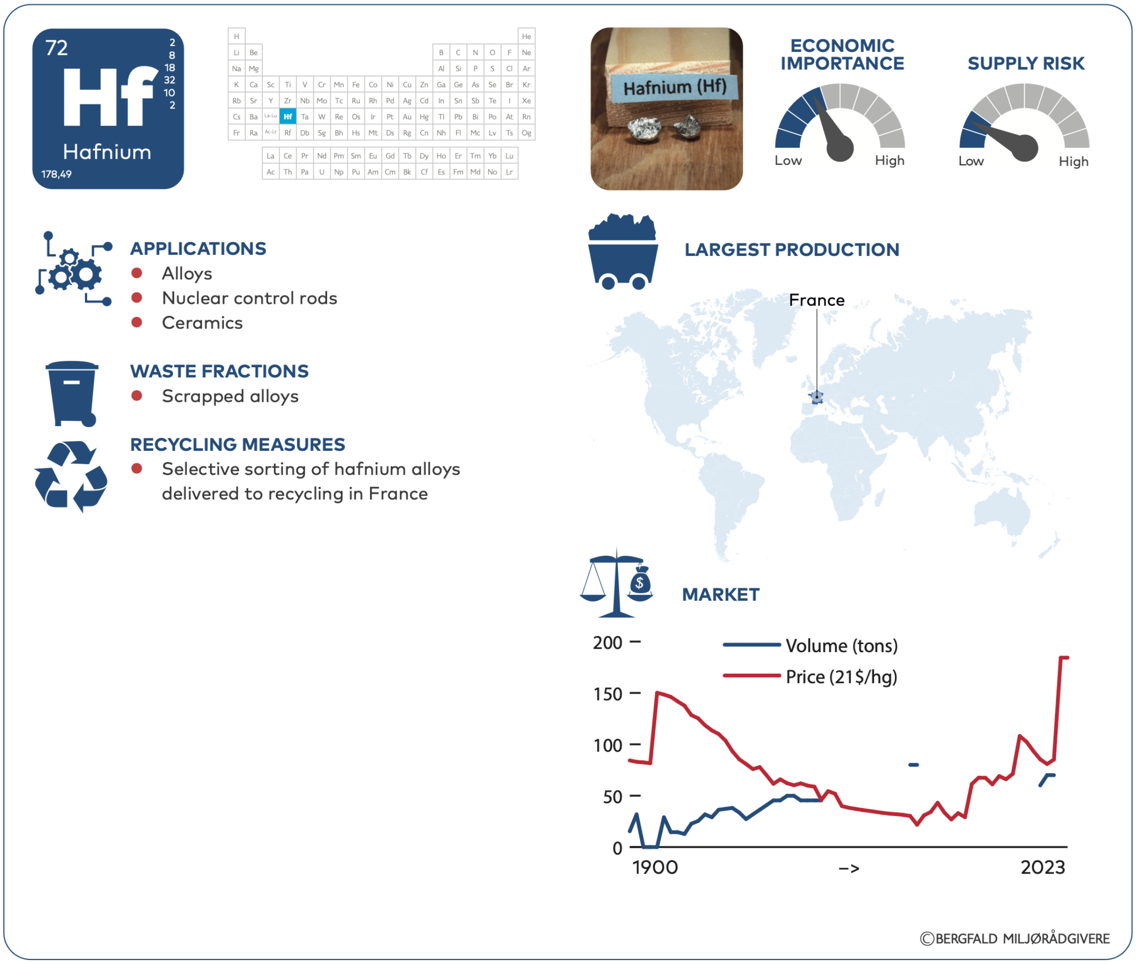
Germanium is a chemical element with atomic number 32 and has an appearance similar to silicon. The metalloid is a semiconductor with many electronic applications. Germanium is the 50th most common element in the Earth's crust and is mined primarily from the mineral sphalerite, which is also an ore for zinc, but can also be extracted from silver, lead, and copper ores. China is the world's largest producer of germanium. The global production in 2021 was about 180 tons.

The main applications of germanium are in fiber-optic systems to prevent loss of signal, infrared optics, solar cell applications, and light-emitting diodes (LEDs) and as catalysts for polymerization reactions.

Waste streams and systems for recycling

The European recycling rate of germanium is estimated to be about 2%. There are no significant germanium recycling operations in the Nordics.

Hafnium



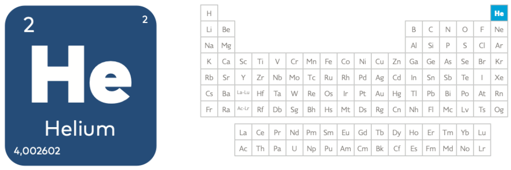
Applications and market situation

Hafnium is a chemical element with atomic number 72. The transition metal has similar chemical properties with zirconium, and the two elements are geologically found together. The most important minerals are zircon and baddeleyite where zirconium and hafnium are typically present in the ratio 50:1. The production of hafnium is for this reason strongly linked to the production of zirconium. Europe is the largest producer of hafnium, with France as the leading producer and exporter of hafnium. Hafnium is used in high temperature ceramics, and the metal is also used in nickel alloys, for plasma-based metal processing and in the nuclear power sector. In electronic products, hafnium is mainly used in semiconductors and optical parts, but this consumption is low compared to other areas of use. The global production of hafnium in 2017 was estimated to be around 70 tons.

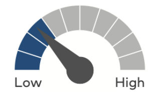
Waste streams and systems for recycling

There is very limited if any recycling of hafnium, and no significant recycling operations for hafnium has been identified in the Nordics.

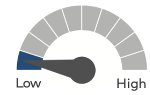
Helium



ECONOMIC IMPORTANCE



SUPPLY RISK

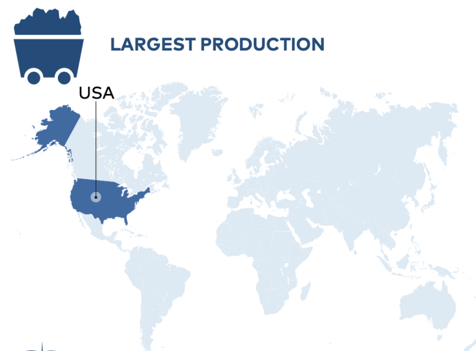


APPLICATIONS
- Welding/blanket gas
- Cryogenics
- MRI
- Atmosphere for deep diving
- Balloons

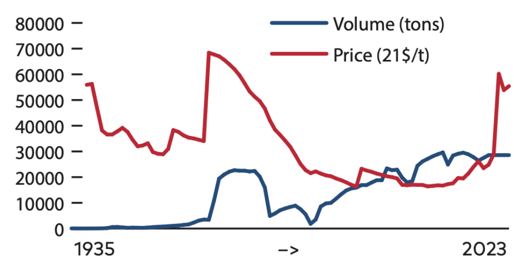
WASTE FRACTIONS
- Spent industrial helium gas

RECYCLING MEASURES
- Establish collection and recycling system of spent helium gas
- Ban on use of helium for entertainment purposes

LARGEST PRODUCTION



MARKET



Applications and market situation

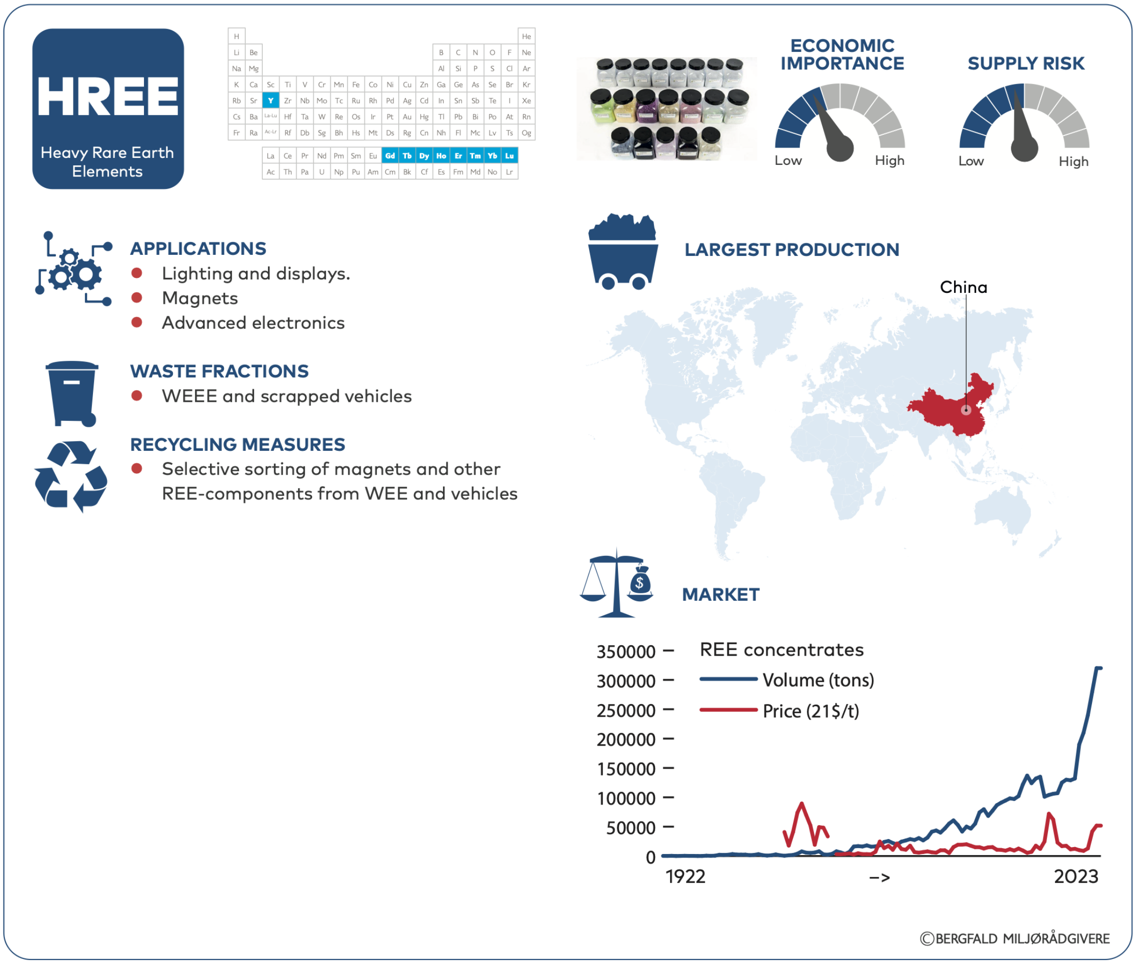
Helium is a chemical element with atom number 2. It is the lightest noble gas and has a lower density than air. Although helium is the second most common element in the universe after hydrogen, the element is far less common on the Earth's surface. All available helium on earth is formed by radioactive alpha radiation from uranium and thorium in geological formations. Most of this helium leaks out through pores and cracks but some helium is trapped in reservoir rocks under mantle rocks, often together with natural gas, from where it can be extracted. All helium is for this reason produced as a byproduct from natural gas production. USA is the dominant global helium producer, followed by Qatar.

Important application of helium is as a cooling gas for extremely low temperatures, and as an inert atmospheric gas in many sensitive industrial processes that cannot tolerate other pollutants. Helium is also used in small volumes in some niche applications like MRI and other advanced medical equipment. Although the total consumption of helium is limited, it is virtually impossible to find substitutions for this noble gas. Therefore, it can be questioned if the large quantities of helium being used for entertainment purposes such as inflating balloons is sensible.

Waste streams and systems for recycling

Helium can be recycled, but this is difficult at low pressures or if helium is diluted through mixture with other gases. Discarded helium gas from, for example, cooling systems and inert atmospheres, however, can be easily reused. Around 1% of the European helium consumption is recycled. There is no significant helium recycling in the Nordics.

Heavy Rare Earth Elements



Applications and market situation

Rare Earth Elements (REE) consists of 15 chemical elements with atomic numbers from 57–71 and are also referred to as the lanthanoid group. The substance group show relatively similar chemical properties, and REE with atomic numbers 62–71 is referred to as heavy (HREE). All HREEs have important industrial applications.

Although most HREEs are not geological rare in a strict sense of the word, they are challenging to produce because they are not found concentrated in ores. Instead, they are more evenly distributed throughout the Earth's crust. Due to HREEs having very similar chemical properties, chemical separation is difficult. REE ores will almost always contain all elements except promethium, but in varying ratios, and the market price for various REE metals also varies greatly from metal to metal.

Important applications of HREE include permanent magnets for electric motors and electricity generators, lighting phosphors, catalysts, lasers, glass and ceramics.

Magnetic metals make up around 90% of the value of the REE market, although other markets are equally large in tons. Permanent magnets made of neodymium (Nd) (often alloyed with praseodymium and/or holmium) form the strongest and most consistent magnetic fields, and therefore has a dominant position as a magnetic material, as this provides the greatest energy efficiency for both power generators in wind turbines and electric motors. The Green Shift where wind turbines and electric cars play a role key role, has provided a particularly strong development in the REE market, which is shown both in increasing production volumes and prices, and there is reason to expect that the total REE-market will continue to grow significantly in the coming years.

Today, China practically has complete control over the HREE-market making other countries concerned about this supply risk. All states that have published lists of critical raw materials have listed REE or LREE/HREE as critical materials. The global production of HREE (refined metal) in 2021 was around 12,800 tons.

Waste streams and systems for recycling

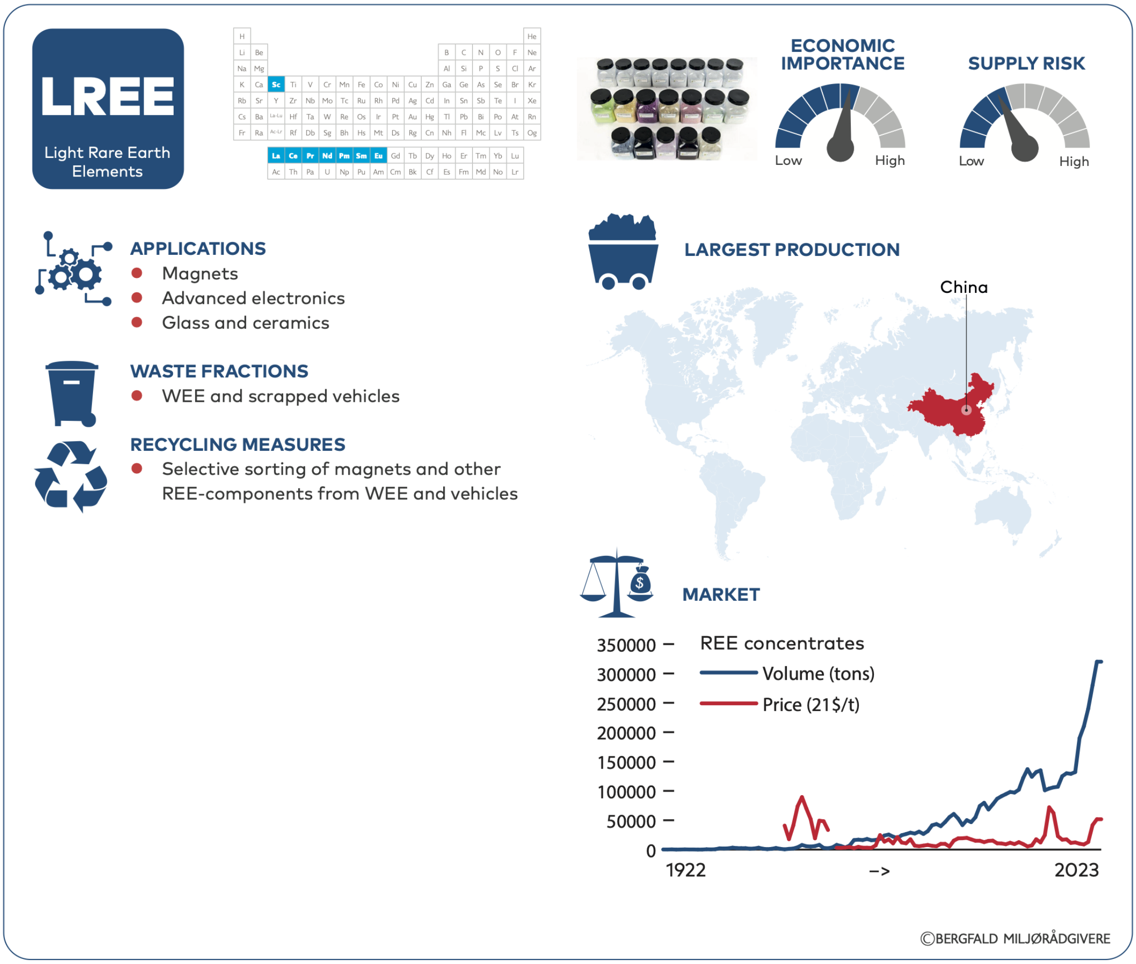
Despite many important applications and the status of China's as the single supplier of REE, there is so far very little recycling of these important metals, and the technology for recycling of HREE from many waste streams is still immature. Global recycling rate for HREE is estimated to be around 4%. There are however significant waste streams available from which HREE can be recovered when this becomes technologically possible and economically advantageous.

LREE and HREE will often exist in the same waste streams, with WEEE and scrapped vehicles being examples of waste streams that may form feedstock for future HREE/LREE recycling. HREE can be found in WEEE in fluorescent tubes, energy saving bulbs, screens, lasers, hard drives, electric motors, advanced batteries, fiber-optic equipment, and various types of electrical measuring equipment.

There is so far no recycling capacity for HREE-waste in the Nordic countries. There is however a LREE-processing plant under construction in Norway, which can be expanded to recycle HREE if provided incentives to do so.[33]

33. Disclosure: One of the report authors is a minority shareholder in the REEtec plant.

Light Rare Earth Elements



Applications and market situation

Rare Earth Elements (REE) consists of 15 chemical elements with atomic numbers from 57–71, also referred to as the lanthanoid group. The substance group has relatively similar chemical properties, and the elements with it atomic numbers 57–61 are referred to as light (LREE). All the LREE elements have important industrial applications except promethium, which is radioactive and so unstable that it is not available for industrial use.

Although most HREEs are not geological rare in a strict sense of the word, they are challenging to produce because they are not found concentrated in ores. Instead, they are more evenly distributed throughout the Earth's crust. Due to LREEs having very similar chemical properties, chemical separation is difficult. REE ores will almost always contain all elements except promethium, but in varying ratios, and the market price for various REE metals also varies greatly from metal to metal.

Important applications of LREE include permanent magnets for electric motors and electricity, generators, lighting phosphors, pigments, catalysts, glass and ceramics.

Magnetic metals make up around 90% of the value of the REE market, although other markets are equally large in tonnes. Permanent magnets made of neodymium (Nd) (often alloyed with praseodymium and/or holmium) form the strongest and most consistent magnetic fields, and therefore has a dominant position as a magnetic material, as this provides the greatest energy efficiency for both power generators in wind turbines and electric motors. The Green Shift where wind turbines and electric cars play a role key role, has provided a particularly strong development in the REE market, which is shown both in increasing production volumes and prices, and there is reason to expect that the total REE-market will continue to grow significantly in the coming years.

Today, China practically has complete control over the LREE-market making other countries concerned about this supply risk. All states that have published lists of critical raw materials have listed REE or LREE/HREE as critical materials. The global production of LREE (refined metal) in 2021 was around 162,000 tons.

Waste streams and systems for recycling

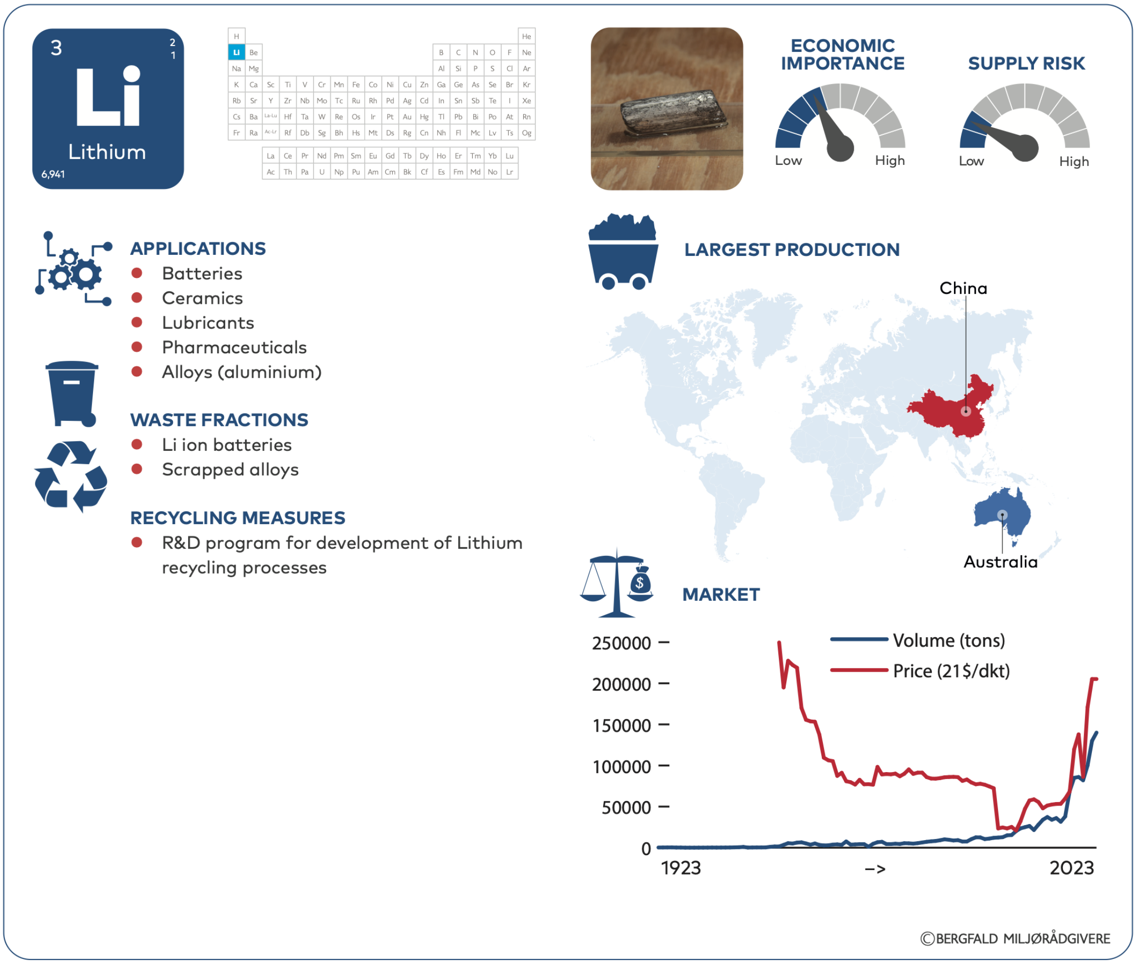
Despite many important applications and the status of China's as the single supplier of REE, there is so far very little recycling of these important metals, and the technology for recycling of LREE from many waste streams is still immature. Global recycling rate for LREE is estimated to be around 3%. There are however significant waste streams available from which LREE can be recovered when this becomes technologically possible and economically advantageous.

LREE and HREE will often exist in the same waste streams, with WEEE and scrapped vehicles being examples of waste streams that may form feedstock for future LREE/HREE recycling. LREE can be found in WEEE in fluorescent tubes, energy saving bulbs, screens, lasers, hard drives, electric motors, advanced batteries, fiber optic equipment, and various types of electrical measuring equipment.

There is so far no recycling capacity for LREE-waste in the Nordic countries. There is however a LREE-processing plant under construction in Norway, which can be expanded to recycle LREE if provided incentives to do so.[34]

34. Disclosure: One of the report authors is a minority shareholder in the REEtec plant.

Lithium



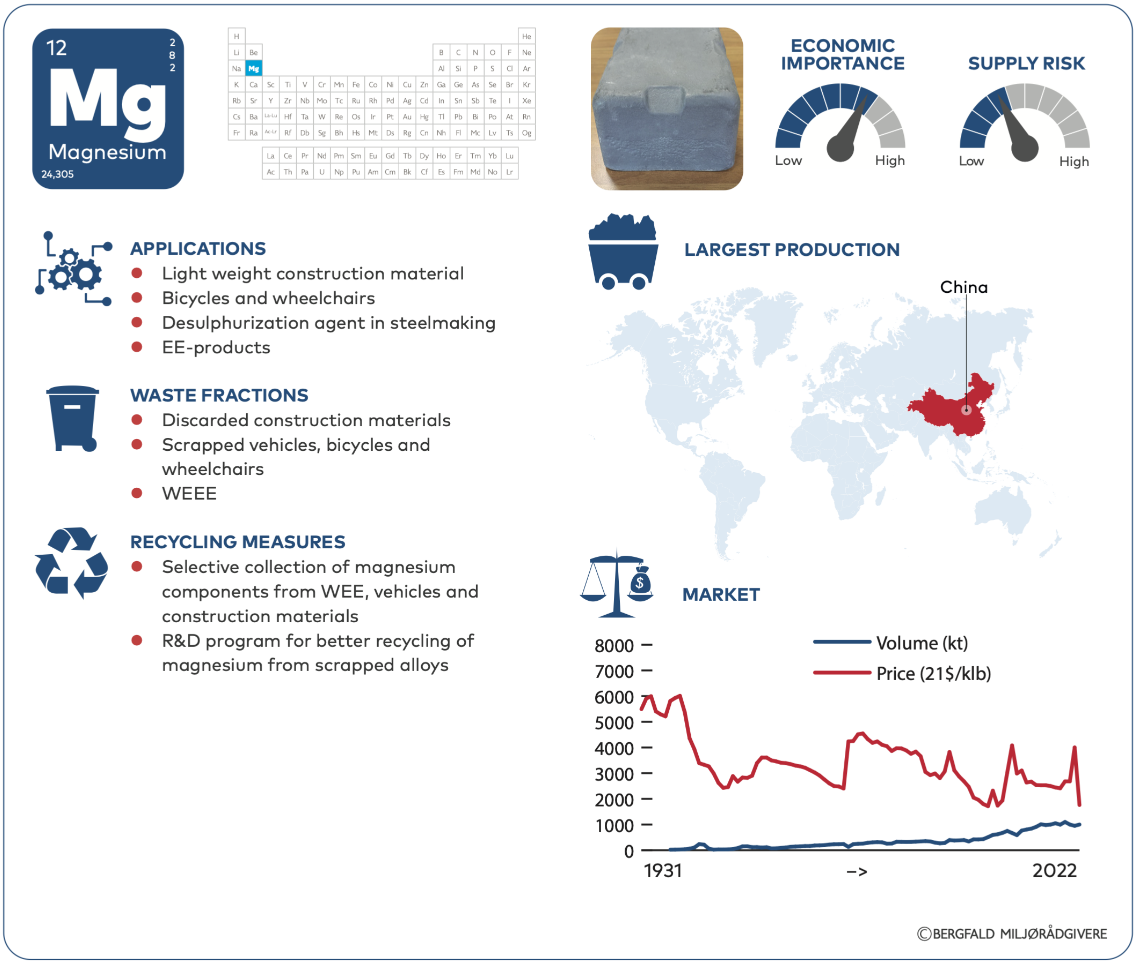
Applications and market situation

Lithium is a silver-white alkali metal with atomic number 3 that has low density and material strength, and the lowest electronegativity of all elements, which gives the element unique chemical properties. Lithium has many applications, including as an additive for glass and ceramic materials, in metallurgical processes, in lubricants and optical materials. However, the largest area of use in recent years are for batteries, and this consumption is expected to grow significantly in the coming years. While lithium was a niche metal only a few years ago with total global consumption of just under 10,000 tonnes per year, consumption has since increased dramatically and the global production of refined lithium in 2020 reached 339 000 tons. There are significant deposits of lithium in a number of places in the world, with large production in Atacama in South America (spread over three countries) and Greenbushes in Australia. China is also one of the largest producers of lithium.

Waste streams and systems for recycling

No significant recycling of lithium occurs in the world, although technologies for recovery of lithium from batteries are being developed. There is recycling capacity for post-consumer lithium batteries in the Nordics. Although these processes so far do not recover lithium but focus on extracting metals such as nickel and cobalt, the infrastructure for recycling of lithium is established. Recycling technology from batteries that include lithium is expected to be applied in the near future. The recycling process for recovery of lithium from batteries will most likely be energy intensive, and could therefore be suitable at Nordic locations with readily available surplus of electricity.

Magnesium



Applications and market situation

Magnesium is a silver white metal with atomic number 12. The light weight and high material strength of magnesium gives magnesium many applications as construction material in vehicles and in aviation. Magnesium alloys are also used in consumer electronics for example in chassis for laptops, mobile phones, camera housings or handhelds tools such as drills, screwdrivers or chainsaws. The global magnesium market is about 1 million tons with China being the largest producer.[35]

Waste streams and systems for recycling

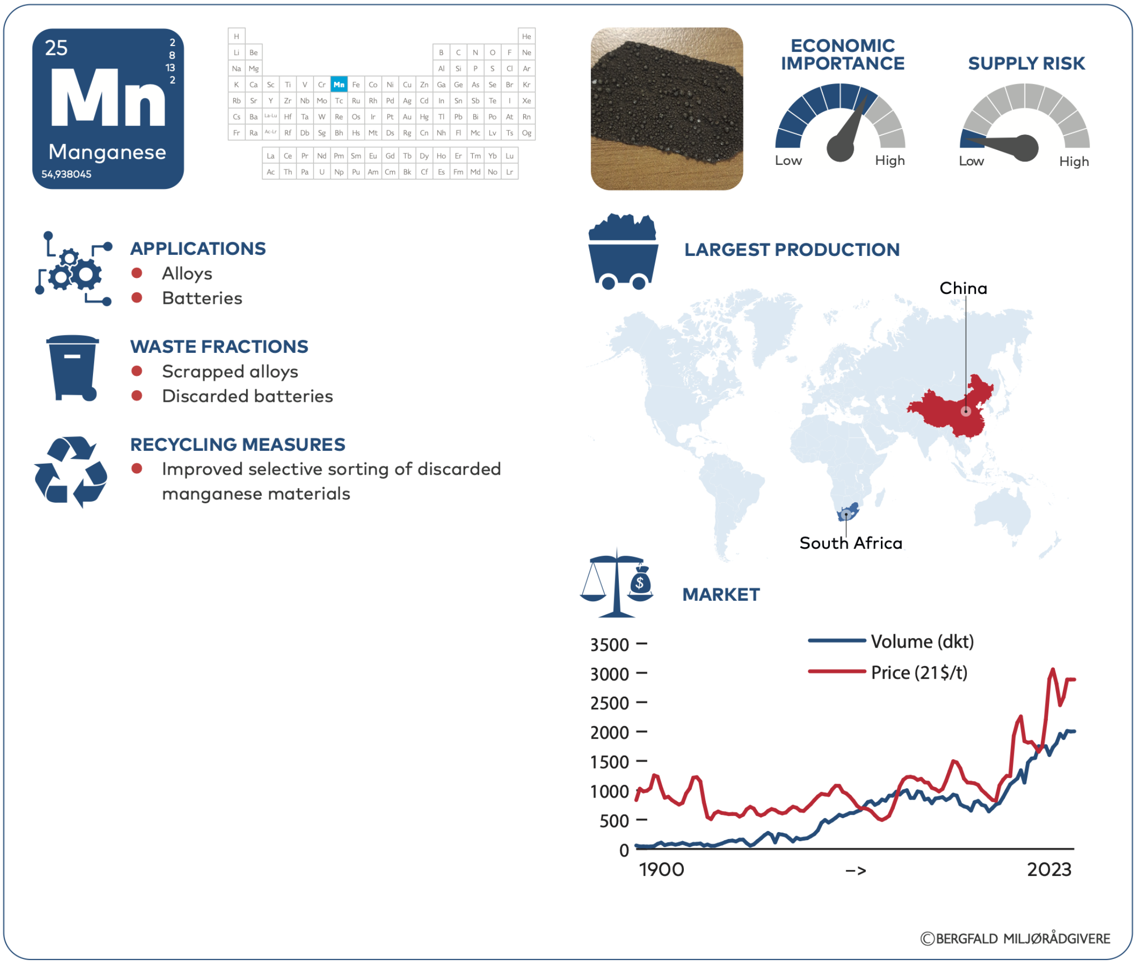
European recycling rate of magnesium is estimated to be around 7 %. There is no recycling capacity however for post-consumer magnesium in the Nordic countries, although other European countries have a substantial capacity for recycling both sorted magnesium components and industrial scrap. Magnesium alloys are often

35. United States Geological Survey

tailor-made to their applications, which can make it challenging to achieve the desired chemical composition for secondary magnesium alloys, although magnesium and aluminum alloys do have considerable tolerance for each other. Magnesium recycling is further complicated by the fact that many magnesium components in discarded consumer products are varnished, and that magnesium dust is highly explosive.

Until 2005, there was a recycling operation in Norway for complex magnesium scrap, able to handle a wider range of waste than what is currently available in Europe. This plant is currently idle and possible to restart – given the right incentives. There is a substantial consumption of magnesium as an alloying element in the Nordic aluminium and steel industries of more than 20,000 tons that could have been converted from primary to secondary magnesium – if the necessary incentives were provided, which would reduce Nordic dependency on the current three primary magnesium suppliers to Europe; China, Israel and historically Russia.

Manganese



Applications and market situation

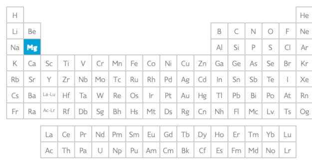
Manganese is a chemical element with atom number 25. The metal is silvery white, hard and brittle and has many industrial applications. The global manganese market is around 20 million tons, with China and South Africa as the largest producer. The main application of manganese is as an alloying agent in steel, but it is also an important raw material for batteries and as anode material in electric cars. Manganese is also a minor component in some fertilizers.

Waste streams and systems for recycling

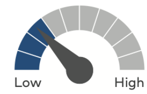
Manganese has a recycling rate of around 9%. There is a Nordic recycling capacity for manganese through the Norwegian Eramet smelters located at Sauda, Kvinesdal and Porsgrunn, and at Ferroglobes smelter in Mo i Rana where manganese batteries and other waste materials with high levels of manganese could potentially be recycled.

Natural Graphite

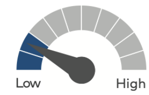
6 2 4
C
Carbon
12,0107



ECONOMIC IMPORTANCE



SUPPLY RISK



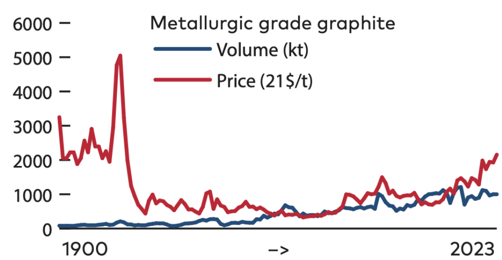
APPLICATIONS
- Batteries
- Electrodes and refractory material for foundries and metal production
- Alloys
- Lubricant

WASTE FRACTIONS
- Discarded batteries
- Spent industrial refractories

RECYCLING MEASURES
- R&D program for recycling of graphite from batteries
- R&D program for recycling of graphite from spent industrial refractories

LARGEST PRODUCTION

MARKET



Applications and market situation

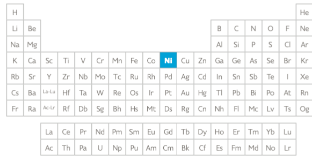
Graphite is one of two allotropic forms that the element carbon occurs in and is found as a mineral in the Earth's crust. Graphite is gray to black in color, soft, non-elastic and has often a metallic sheen. Natural graphite occurs in both crystalline, amorphous and flaky form. Graphite can also be produced industrially from other chemical compounds and is then referred to as synthetic. Graphite is chemical inert and has the greatest electrical and thermal conductivity among the non-metallic elements. The combination of graphite's ability to conduct electricity and thermal stability has given the material important applications in batteries, fuel cells and refractory products. Important areas of use for graphite are also found within the steel industry and other metallurgical industries. Amorphous and flaking graphite is included in the production of lubricants and for construction parts within the automotive industry, electronics and the construction sector. The global annual consumption of graphite is around 1,3 million tons, with China being the largest producer.

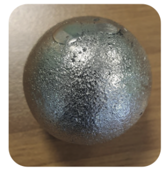
Waste streams and systems for recycling

Only around 3% of used graphite is recycled, and this is mostly refractory materials. Although lithium batteries contain around 16–22% graphite, this graphite is often oxidized to CO_2 during the pyrometallurgical processes used for recycling of batteries, which means the graphite material is lost. Tests have shown that graphite can be separated from lithium and other metals in the electrode material from batteries, and several methods for recycling graphite from used lithium batteries have been patented. Graphite can also be synthesized from other carbon compounds, including CO_2.

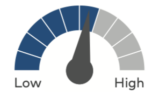
Nickel – battery grade

28
2
8
16
2
Ni
Nickel
58,6934





ECONOMIC IMPORTANCE



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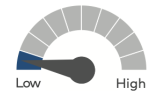


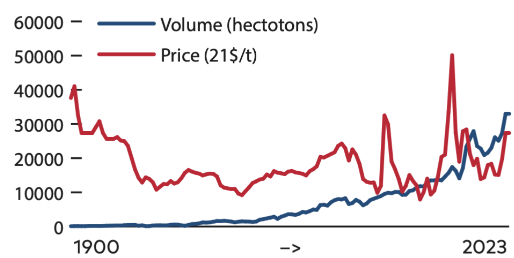
APPLICATIONS
- Alloy
- Metal coating
- Batteries
- Catalyst

WASTE FRACTIONS
- Scrapped alloys and nickel coated materials
- Discarded batteries
- Spent catalysts

RECYCLING MEASURES
- Selective sorting of nickel alloys and batteries

LARGEST PRODUCTION

MARKET



Applications and market situation

Nickel is a silver-white metal with atomic number 28 that is stable at high temperatures and resistant to oxidation in air. The largest application of nickel is as an alloying addition in stainless steel, in galvanic coatings, as catalysts for organic chemical reactions/processes and in batteries. Increased use of nickel in lithium batteries for vehicles means that the consumption of nickel is expected to rise. Nickel is produced from silicate- and sulphide-containing minerals, with Indonesia being the largest producer with approximately one third of the total nickel extraction in the world in the form of ferronickel. The Philippines accounts for around 20% of the global extraction but delivers all extracted ore directly to China which is the largest global processor of nickel.

Waste streams and systems for recycling

The European recycling rate of nickel is estimated to be around 16%, and recycling is performed through both pyrometallurgical and hydrometallurgical processes. There is a large and well developed Nordic capacity for nickel recycling. The Nikkelverk plant in Norway and Boliden plant in Harjavalta are both able to receive high-nickel feedstock for recycling. Indeed, both have declared their intention to increase the secondary feedstock supplies if such materials become available.

Niobium

Applications and market situation

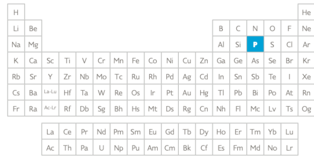
Niobium is a gray and ductile metal with atomic number 41 and its consumption is largely in the form of ferroniobium as an additive to steel to withstand high temperatures. Niobium also has important niche applications in EE products. The world market for niobium is around 120,000 tons, with Brasil being the largest producer.

Waste streams and systems for recycling

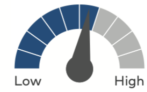
A limited recycling industry for industrial niobium scrap, superconducting materials and larger components and alloys does exist, although there is no recycling capacity for postconsumer niobium or niobium-containing materials in the Nordic countries.

Phosphate rock

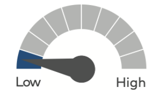
Phosphate rock



ECONOMIC IMPORTANCE



SUPPLY RISK



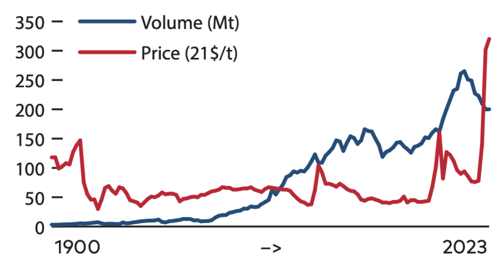
APPLICATIONS
- Syntetic fertilizer
- Nutrient additive
- Flame retardant

WASTE FRACTIONS
- Food and foodprocessing waste
- Agricultural waste
- Bioresidue from biogas production

RECYCLING MEASURES
- Ban on incineration of food waste
- Statutory delivery obligation for animal manure and fishery waste to biogas production
- Extraction of phosphate from bioresidue from biogas production that cannot be utilized as fertilizer applied as feedstock for phosphate recycling
- Extraction of phosphate from ashes and waste water sludge

LARGEST PRODUCTION

MARKET



Applications and market situation

Phosphate (PO_4^{3-}) is the anion of phosphoric acid and is an essential nutrient for all living organisms. Phosphate is also a chemical precursor for production of many phosphoric chemicals with applications that include food additives, detergents and flame retardant. The most important application is however as fertilizer. Phosphate is mined from various phosphate rocks, and the largest producer of phosphate is China. The global production of phosphate rock is around 75 million tons.

Waste streams and systems for recycling

Phosphate is found in organic waste and industrial waste containing phosphorous acid and chemical derivatives of this acid. The European recycling rate of phosphate is estimated to be around 17%. In agricultural waste phosphate is both found bound in organic matter and as residues of fertilizers. The dominant method for recycling of phosphate seems to be through biogas production where the nutrient-rich residue from the anaerobe digestion process can be used as phosphate rich fertilizer. All Nordic countries have extensive biogas production. There are also interesting projects extracting phosphate from incineration ashes and wastewater.

Phosphorus

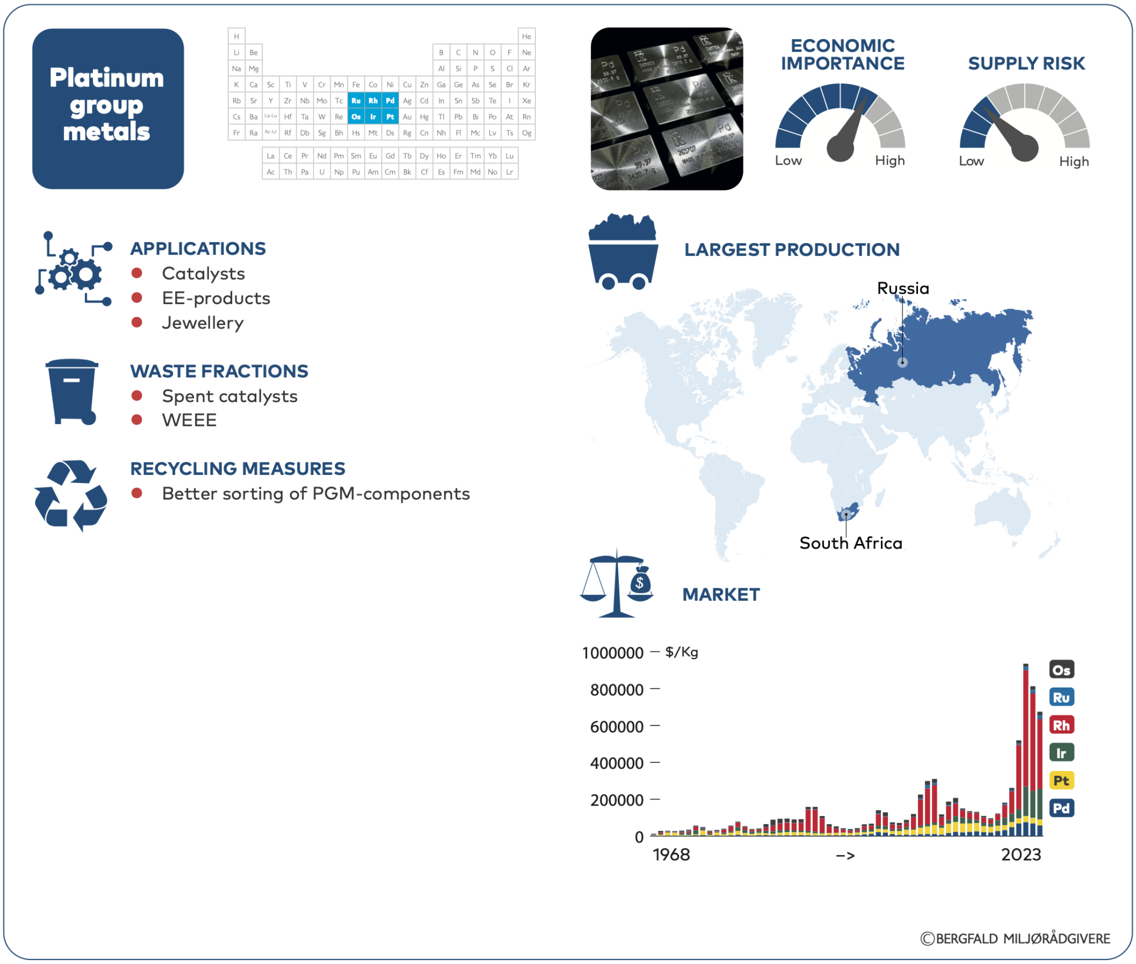
Applications and market situation

Phosphorus is a chemical element with atomic number 15 that exists as in several allotropic forms including white and red phosphorus. Due to its chemical reactivity elementary phosphorous is never found in nature but occurs mainly as phosphate minerals. Phosphorus has important industrial and defense applications. China is the dominant producer of phosphorous. The global production of phosphate rock is around 1,200 tons.

Waste streams and systems for recycling

Because phosphorous is very reactive, most spent elemental phosphorous will be converted to other chemical compounds. There is no significant direct recycling of spent phosphorus, and recycling from phosphate may be a more rational pathway.

Platinum Group Metals



Applications and market situation

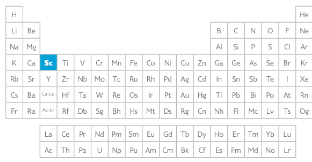
The platinum-group metals (PGMs) consist of six chemical elements where five is listed as critical by EU. These precious metals include ruthenium, rhodium, palladium, iridium, and platinum. PGMs are very rare in the Earth's crust and are typically found together in the same ores. Important applications of PGMs include use as catalysts and electronic components. South Africa and Russia are the main producers of PGMs. Global production of PGMs was around 640 tons in 2021.

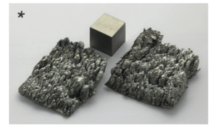
Waste streams and systems for recycling

Despite their high value, the European PGM recycling rate is estimated to be only around 30%. One reason for this is that many PGM applications involve use of small amounts that are hard to recover from other materials they are mixed with. There is substantial recycling capacity for PGM metals in the Nordics. The Nikkelverket plant in Norway, Boliden Rönnskär in Sweden and Boliden Harjavalta in Finland are all able to receive different PGM-containing secondary feedstocks for processing. The K.A. Rasmussen plant in Norway is able to process high grade metals such as industrial catalysts.

Scandium

21 2 8 9 2
Sc
Scandium
44,955912

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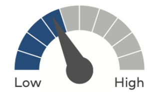
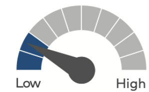
ECONOMIC IMPORTANCE



SUPPLY RISK



APPLICATIONS
- EE-products
- Solid Oxide Fuel Cells
- Light weight alloys

WASTE FRACTIONS
- Scrapped alloys
- WEEE

RECYCLING MEASURES
- R&D program for better recycling of scan-dium from scrapped alloys

LARGEST PRODUCTION

Applications and market situation

Scandium is a chemical element with atomic number 21. The metal has a silvery-white appearance. Scandium is present in most of the deposits of rare-earth and uranium compounds. The global trade of scandium is small, only about 20 tons per year, and its main application is as addition in aluminium alloys. Other minor applications include use in EE-products and fuel cells.

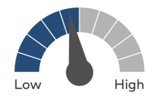
Waste streams and systems for recycling

There is no recycling capacity for postconsumer scandium or scandium-containing materials in the Nordic countries.

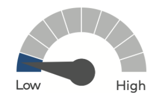
Silicon metal

14
Si
Silicon
28,0855
2 8 4

ECONOMIC IMPORTANCE



SUPPLY RISK



APPLICATIONS
- Alloys
- Chemicals
- Photovoltaics
- Semiconductors/Microchips

WASTE FRACTIONS
- Scrapped solar panels
- WEEE

RECYCLING MEASURES
- R&D program for recycling of silicon from scrapped solar panels

LARGEST PRODUCTION

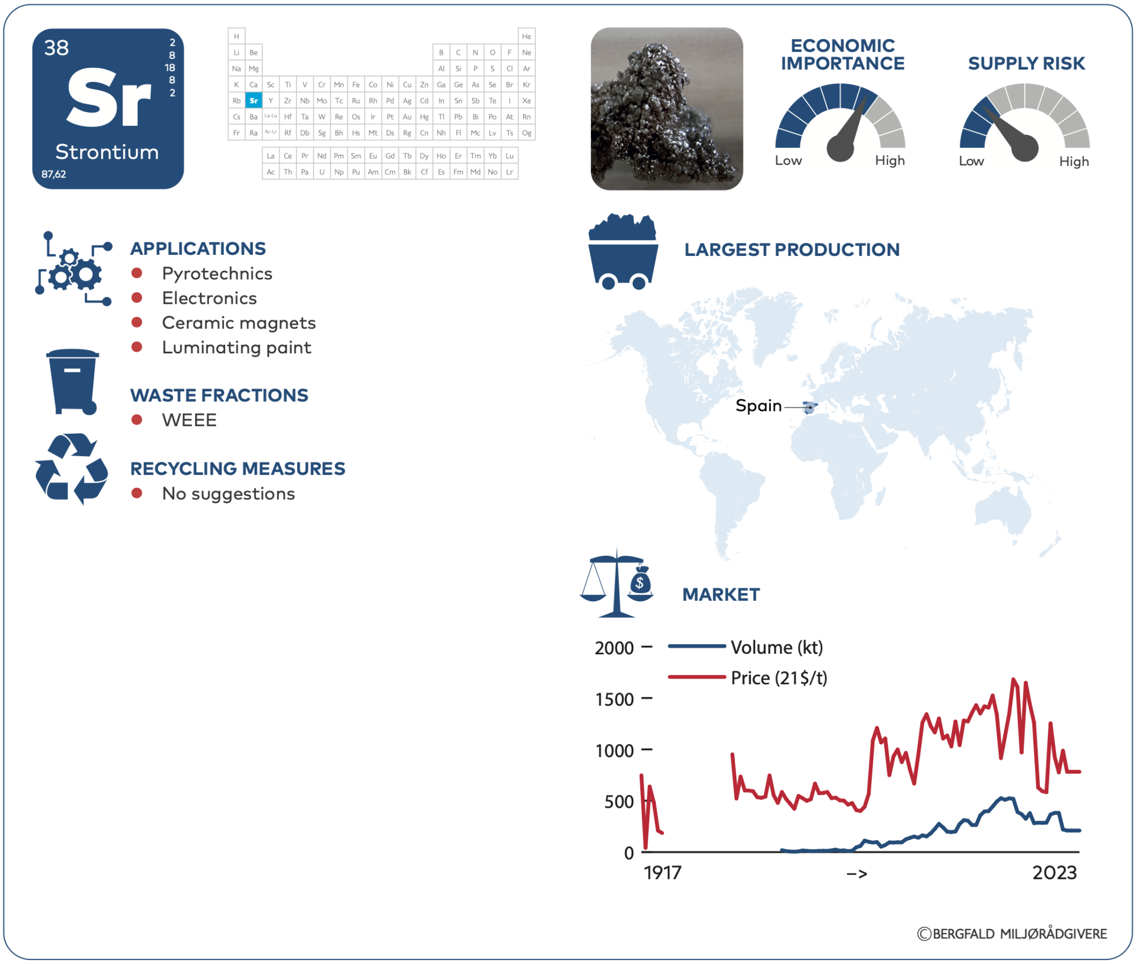
Applications and market situation

Silicon is a chemical element with atomic number 14. The metalloid has a blue-grey shine and good properties as a semiconductor with many important industrial applications that include photovoltaics and micro-chips. Silicon is the most common chemical element in Earth's crust after oxygen. China is the largest producer of silicon. The global production of silicon metal in 2021 was around 3,3 million tons.

Waste streams and systems for recycling

There is no recycling capacity for postconsumer silicon or silicon-containing materials in the Nordic countries. There is however a substantial industry for production of primary silicon that may be fitted for recycling operations.

Strontium



Applications and market situation

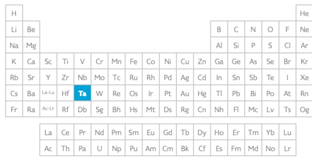
Strontium is a chemical element with atom number 38. The alkaline earth metal is soft and has a white or yellowish appearance and is highly chemically reactive. Applications of strontium include use in pyrotechnics, ceramic magnets, magnets and luminating paint. Strontium is mainly mined from the minerals celestine and strontianite with Spain and Iran as dominant producers. The global production of strontium in 2021 was around 580,000 tons.

Waste streams and systems for recycling

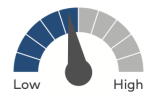
There is no recycling capacity for postconsumer strontium or strontium-containing materials in the Nordic countries. The European recycling rate of strontium is also zero.

Tantalum

73
2
8
18
32
11
2
Ta
Tantalum
180,94788



ECONOMIC IMPORTANCE



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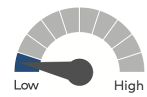


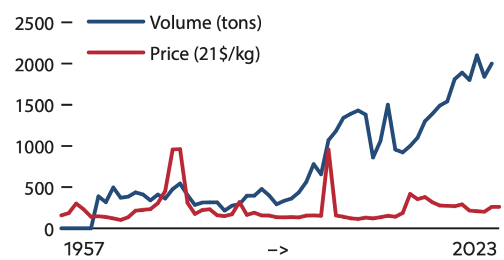
APPLICATIONS
- Medical and laboratory equipment
- Alloys
- EE-products (capacitors and cocking elements)

WASTE FRACTIONS
- WEEE

RECYCLING MEASURES
- Separate collection of capacitors and cocking elements from WEE

LARGEST PRODUCTION

MARKET



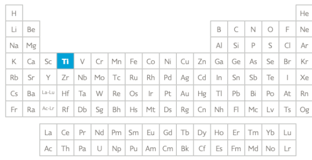
Applications and market situation

Tantalum is a chemical element with atomic number 73. The metal is hard ductile and chemically inert with a blue-gray appearance. Important applications include use in capacitors for electronic devices, cooking elements and super alloys. In nature tantalum is found in ores together with niobium in minerals like tantalite, columbite and coltan. The main producer of tantalum is Kongo DRC. The global production of strontium in 2018 was around 2,200 tons.

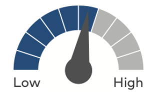
Waste streams and systems for recycling

The European recycling rate of tantalum is estimated to be 13%. There is no recycling capacity however for postconsumer tantalum or tantalum-containing materials in the Nordic countries.

Titanium metal



ECONOMIC IMPORTANCE



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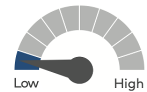


APPLICATIONS
- Alloys
- Light weight construction metal
- EE-products

WASTE FRACTIONS
- Scrapped alloys
- WEEE

RECYCLING MEASURES
- Better selective sorting of titanium alloys

LARGEST PRODUCTION

Applications and market situation

Titanium is a chemical element with atomic number 22. The metal has a silvery color, and has high material strength, low density and is resistant to corrosion. Important applications of titanium metal include medical implants, EE-products, light weight alloys and military, aeronautics and space applications. In nature titanium is found in minerals like ilmenite and rutile. China is the largest global producer of titanium metal. The global production of titanium metal in 2021 was around 244,000 tons.

Waste streams and systems for recycling

Around 6% of titanium metal is recycled, but there is so far no recycling capacity for post-consumer titanium or titanium-containing materials in the Nordic countries. There is from time to time the use of titanium metal turnings in the production of primary aluminium alloys. However, this is industrial scrap, a globally traded byproduct.

Tungsten

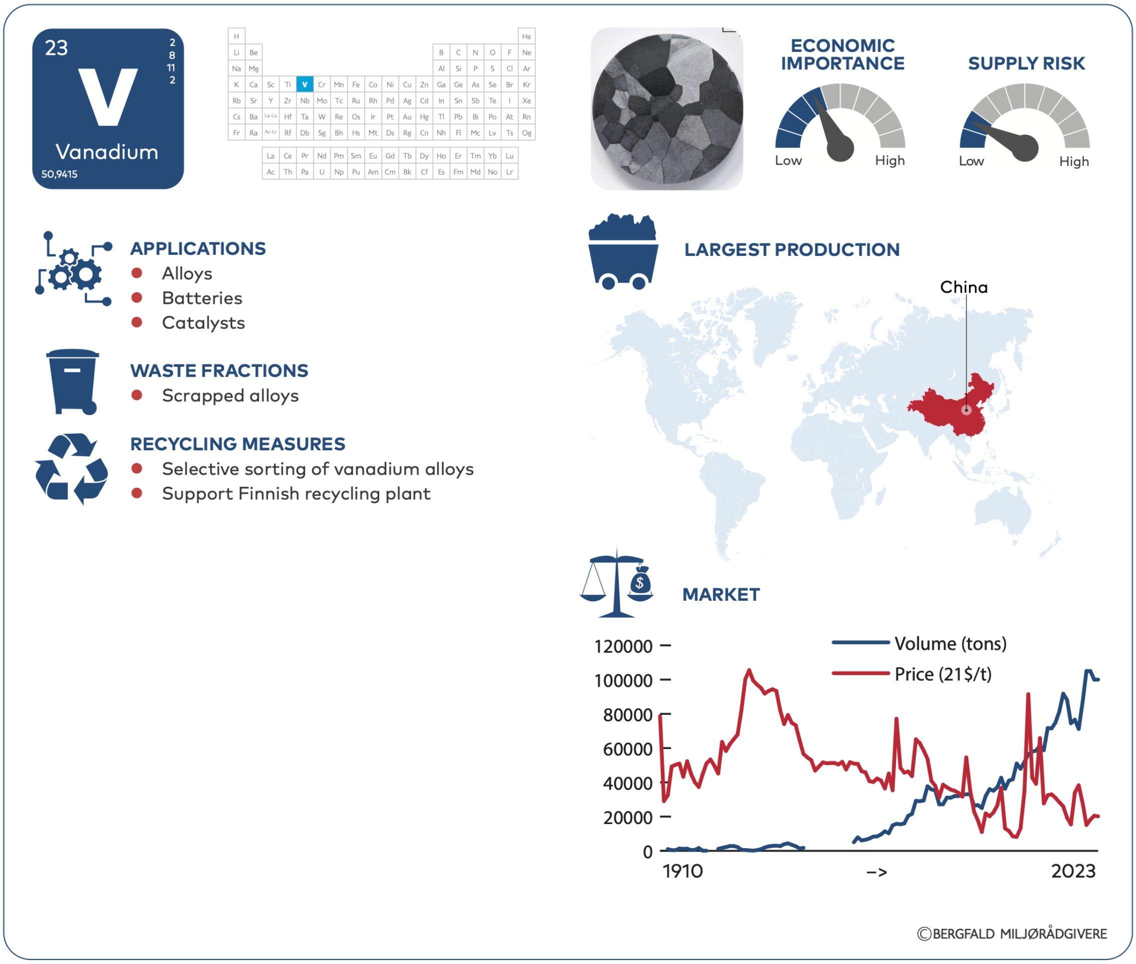
Applications and market situation

Tungsten is a chemical element with atomic number 74. The metal is hard and have a high density and the highest melting point of all known elements. Tungsten has important applications in super alloys, electronic equipment, coating of cutting and drilling bits, electrodes in gas tungsten arc welding, catalyst and projectiles. Its important ores include scheelite and wolframite, the latter lending the element its alternate name. China is the largest producer of tungsten. The global production of tungsten in 2021 was around 100,000 tons.

Waste streams and systems for recycling

There are well developed recycling systems for tungsten that have a reported recycling rate of 42%. Recycling in the Nordics is organized by the Swedish company Sandvik. The key recycling furnace is in Austria, and Sandvik operate a collection scheme. Increased tungsten recovery from WEEE is possible.

Vanadium



Applications and market situation

Vanadium is a chemical element with atomic number 23. The metal is hard, silvery-grey and malleable. Important applications include use in batteries, catalysts and alloys. Vanadium is mainly produced from steel smelter slag with China and Russia being the main global producers. The global production of vanadium in 2021 was around 116,000 tons.

Waste streams and systems for recycling

Very little vanadium is recycled globally, and European recycling rate is estimated to be 1%. There is no recycling capacity for postconsumer vanadium or vanadium-containing materials in the Nordic countries. Neometals in Finland have a project to upgrade vanadium-containing blast furnace slags currently produced and landfilled in Sweden and Finland to a commercial ferrovanadium alloy.

Appendix 2 Nordic CRM enriched waste streams

The following paragraphs presents a quantitative description of Nordic waste streams that are known to contain CRM-enriched materials. To get a best possible overview of the CRM potential, we have approached the possible resources from two different approaches; top down and bottom up. The top-down description covers overall waste streams that contain CRM-enriched sub streams for the last three years, as reported by Eurostat. These numbers are reported by the industry itself according to the waste codes and aggregated. As a bottom-up description, specific numbers for each of the key industries or waste categories that are known to contain or carry CRMs have been collected and aggregated up to each national levels. The comparison of the top down and bottom-up numbers makes it possible to evaluate CRM strategies both from an overall political approach as well as a highly practical approach.

CRM-waste streams in Norway

Table A1 Norwegian overall waste streams, Source: Eurostat

Norway

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	328.881	304.992	346.759
Chemical wastes	368.651	204.742	272.965
Industrial effluent sludges	87.687	101.216	92.044
Combustion wastes	632.402	758.079	751.670
Spent solvents	16.188	16.101	15.721
Used oils	89.290	37.722	59.310

Biological waste			
Animal and mixed food waste	407.769	581.508	484.602
Animal faeces, urine and manure	0	0	0
Vegetal wastes	185.713	181.885	197.160
Common sludges	214.780	232.164	280.703
Health care and biological wastes	1.836	297	459
Metallic waste			
Metal wastes, ferrous	105.387	130.725	66.157
Metal wastes, mixed ferrous and non-ferrous	461.887	726.161	496.637
Metal wastes, non-ferrous	236.987	1.234	8.550
Non-metallic sorted materials			
Glass wastes	124.135	144.456	117.362
Plastic wastes	244.217	275.537	254.853
Rubber wastes	58.405	61.824	43.348
Textile wastes	3.064	6.180	2.858
Wood wastes	855.518	802.333	898.825
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	153.456	137.326	170.816
Discarded vehicles	216.205	230.783	211.666
Batteries and accumulators wastes	22.012	22.949	23.890

Mixed waste			
Household and similar wastes	1.011.736	926.382	958.400
Mixed and undifferentiated materials	1.847.714	1.744.418	1.326.307
Mineral waste			
Mineral waste from construction and demolition	2.395.057	2.427.875	2.976.397
Other mineral wastes (W122+W123+W125)	0	189.327	214.129
Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	73.418	122.881	125.065
Sludges and liquid wastes from waste treatment	0	904	318
Sorting residues	194.165	270.692	286.699
Soils	42.613	2.702.226	2.749.005

Table A2 Norwegian CRM enriched waste streams

Norway: Elements in waste

	Total	WEEE	Batteries	Ashes	Cars&-Tires	Tailings	Iron/Steel	Non-Ferrous Industries	Other
Antimon	1.286	56	707	85	24	-	42	371	2
Arsen	982	5	18	19	6	1	44	876	13
Barium	7.902	110	2	1.324	507	1.506	3.098	1.233	122
Beryllium	6	0	0	1	0	-	3	2	1
Bor	603	69	6	156	32	1	325	2	13
LREE	974	157	46	85	28	486	93	31	47

HREE	165	22	1	15	9	0	56	41	19
PGM	22	5	-	0	2	-	-	15	0
Fluor	15.398	31	1	128	42	-	942	14.074	180
Fosfor	21.989	21	34	4.420	155	16.815	208	208	128
Gallium	88	4	-	6	2	0	7	65	3
Germanium	6	0	-	1	0	0	0	5	0
Hafnium	10	2	-	2	3	0	2	0	1
Kobber	16.261	9.562	377	2.404	2.650	366	96	784	22
Kobolt	812	53	473	16	46	179	13	24	7
Litium	495	7	121	35	21	0	21	285	5
Mangan	28.261	22	548	4.351	311	12.444	9.320	1.220	46
Nikkel	2.004	126	545	80	59	761	147	258	28
Niob	51	1	0	6	3	15	25	0	2
Scandium	36	0	0	22	0	5	6	2	2
Tantal	48	17	-	1	8	-	3	19	0
Vanadium	1.343	2	0	28	10	692	216	272	125
Vismut	128	9	1	14	1	-	38	65	0
Wolfram	57	7	0	24	12	-	11	1	3

CRM-waste streams in Sweden

Table A3 Swedish overall waste streams, Source: Eurostat

Sweden

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	252.352	321.110	335.356
Chemical wastes	593.427	650.224	929.046
Industrial effluent sludges	166.893	210.847	152.345
Combustion wastes	1.809.785	1.355.965	1.266.815
Spent solvents	24.737	31.878	32.050
Used oils	147.184	170.435	247.258
Biological waste			
Animal and mixed food waste	716.394	730.183	667.131
Animal faeces, urine and manure	759.924	911.776	991.161
Vegetal wastes	902.819	836.897	926.977
Common sludges	400.015	416.745	449.986
Health care and biological wastes	5.677	5.858	4.845
Metallic waste			
Metal wastes, ferrous	1.615.920	2.265.821	1.529.327
Metal wastes, mixed ferrous and non-ferrous	967.446	659.272	679.158
Metal wastes, non-ferrous	148.118	474.398	538.119

Non-metallic sorted materials			
Glass wastes	240.737	250.742	280.665
Plastic wastes	315.976	396.061	342.506
Rubber wastes	87.474	94.508	93.454
Textile wastes	8.646	10.696	12.307
Wood wastes	1.905.525	1.925.568	1.850.463
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	300.475	247.582	278.978
Discarded vehicles	511.942	557.390	535.140
Batteries and accumulators wastes	34.252	28.203	46.471
Mixed waste			
Household and similar wastes	2.282.990	2.382.541	2.241.231
Mixed and undifferentiated materials	886.251	682.602	608.425
Mineral waste			
Mineral waste from construction and demolition	2.837.841	2.876.625	3.259.664
Other mineral wastes (W122+W123+W125)	110.797.571	104.735.962	117.181.652
Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	1.833.855	2.232.832	2.016.174
Sludges and liquid wastes from waste treatment	95.114	154.898	137.861
Sorting residues	3.165.987	2.775.407	2.412.275
Soils	5.414.690	8.885.143	9.125.163
Total	**136.530.762**	**133.504.448**	**147.257.599**

Table A4 Swedish CRM enriched waste streams

Sweden: Elements in waste

	Total	WEEE	Batteries	Ashes	Cars & Tires	Tailings	Iron/ Steel	Non-Ferrous Ind.	Other
Antimon	1.821	60	762	462	103	0	337	95	2
Arsen	4.871	6	20	151	630	3.677	320	56	13
Barium	9.259	118	2	4.303	744	2.282	412	1.275	122
Beryllium	53	0	0	3	0	46	2	0	1
Bor	3.331	74	7	623	47	2.425	143	0	13
LREE	3.603	170	50	207	36	2.664	285	145	47
HREE	1.305	24	1	50	9	927	261	14	19
Fluor	23.319	33	2	601	168	12.135	8.894	1.306	180
Fosfor	107.438	23	37	17.037	480	86.836	2.568	330	128
Gallium	119	4	-	24	1	10	63	13	3
Germanium	5	0	-	2	0	0	1	1	0
Hafnium	24	2	-	10	5	1	5	0	1
Kobber	59.178	10.314	406	9.790	3.026	31.164	588	3.868	22
Kobolt	37.125	57	510	68	46	36.008	81	348	7
Litium	393	8	130	62	150	-	28	11	5
Mangan	148.295	24	591	9.496	435	117.215	18.205	2.285	46
Nikkel	3.961	136	588	341	130	1.171	1.363	203	28
Niob	345	1	0	22	11	82	226	0	2
Scandium	331	0	0	83	0	239	7	0	2

Strontium	2.288	56	0	944	264	684	321	1	19
Tantal	54	18	-	2	8	0	24	0	0
Vanadium	5.148	3	0	128	10	2.387	2.486	10	125
Vismut	359	9	1	62	1	0	286	0	0
Wolfram	403	7	0	81	52	88	172	0	3

CRM-waste streams in Denmark

Table A5 Danish overall waste streams, Source: Eurostat

Denmark

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	13.452	15.692	16.853
Chemical wastes	114.505	111.866	106.334
Industrial effluent sludges	40.056	73.988	124.892
Combustion wastes	749.844	744.919	467.225
Spent solvents	34.539	33.420	19.483
Used oils	30.791	30.710	31.547
Biological waste			
Animal and mixed food waste	183.970	382.768	477.916
Animal faeces, urine and manure	37.841	243.306	247.219
Vegetal wastes	912.094	946.471	1.029.794
Common sludges	174.049	163.059	204.558
Health care and biological wastes	4.799	6.217	7.662

Metallic waste			
Metal wastes, ferrous	798.223	913.741	921.429
Metal wastes, mixed ferrous and non-ferrous	510.895	421.108	408.020
Metal wastes, non-ferrous	73.962	107.770	138.430
Non-metallic sorted materials			
Glass wastes	180.151	203.683	210.087
Plastic wastes	114.585	105.457	139.833
Rubber wastes	38.925	54.862	52.141
Textile wastes	18.134	26.854	18.276
Wood wastes	567.909	696.947	661.573
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	100.059	79.258	95.769
Discarded vehicles	92.702	95.222	73.606
Batteries and accumulators wastes	19.644	15.355	20.811
Mixed waste			
Household and similar wastes	2.474.107	2.466.876	2.355.391
Mixed and undifferentiated materials	338.270	542.093	371.793
Mineral waste			
Mineral waste from construction and demolition	3.460.195	4.127.165	3.780.148
Other mineral wastes (W122+W123+W125)	253.292	222.976	267.397

Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	602.474	586.967	725.615
Sludges and liquid wastes from waste treatment	7.300	7.199	15.012
Sorting residues	471.404	503.919	383.615
Soils	7.750.229	6.764.309	6.087.665
Total	**19.900.753**	**20.347.122**	**19.011.323**

Table A6 Danish CRM enriched waste streams

Denmark: Elements in waste

	Total	WEEE	Batteries	Ashes	Cars & Tires	Tailings	Iron/ Steel	Non-Ferrous Industries	Other
Antimon	1.052	41	516	443	43	-	8	-	0
Arsen	196	4	13	150	14	-	14	-	1
Barium	3.286	80	2	2.831	359	-	6	-	8
Beryllium	5	0	0	4	0	-	0	-	0
Bor	757	50	5	636	63	-	2	-	1
LREE	386	115	34	178	50	-	6	-	3
HREE	83	16	1	46	8	-	9	-	1
PGM	14	3	-	1	9	-	-	-	0
Fluor	834	23	1	625	42	-	131	-	12
Fosfor	30.012	16	25	29.812	124	-	26	-	9
Gallium	22	3	-	16	1	-	2	-	0

Germanium	3	0	-	2	0	-	0	-	0
Hafnium	12	1	-	7	4	-	0	-	0
Kobber	14.183	6.985	275	3.823	3.078	-	21	-	1
Kobolt	466	39	345	50	30	-	2	-	0
Litium	532	5	88	344	94	-	0	-	0
Mangan	11.296	16	400	10.380	186	-	311	-	3
Nikkel	1.219	92	398	589	100	-	37	-	2
Niob	23	0	0	15	4	-	3	-	0
Scandium	13	0	0	12	0	-	0	-	0
Strontium	1.524	38	0	1.412	67	-	6	-	1
Tantal	46	13	-	5	27	-	1	-	0
Vanadium	145	2	0	99	8	-	28	-	8
Vismut	77	6	1	57	1	-	12	-	0
Wolfram	163	5	0	76	80	-	1	-	0

CRM-waste streams in Finland

Table A7 Finnish overall waste streams, Source: Eurostat

Finland

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	112.462	73.131	102.653
Chemical wastes	273.353	305.202	266.371
Industrial effluent sludges	269.084	230.392	251.169
Combustion wastes	1.675.986	1.730.970	1.369.328
Spent solvents	18.247	24.221	64.966
Used oils	37.675	34.535	24.140
Biological waste			
Animal and mixed food waste	665.026	617.557	685.892
Animal faeces, urine and manure	65.382	42.481	46.859
Vegetal wastes	350.924	421.142	450.008
Common sludges	523.759	641.887	417.510
Health care and biological wastes	2.957	3.130	3.531
Metallic waste			
Metal wastes, ferrous	352.274	515.556	320.291
Metal wastes, mixed ferrous and non-ferrous	305.280	275.998	134.473
Metal wastes, non-ferrous	57.546	125.427	109.820

Non-metallic sorted materials			
Glass wastes	137.569	161.302	132.519
Plastic wastes	87.361	120.091	132.105
Rubber wastes	17.000	1.161	882
Textile wastes	14.934	14.456	5.231
Wood wastes	4.738.039	4.371.362	3.135.178
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	73.451	60.762	80.615
Discarded vehicles	118.477	125.988	130.871
Batteries and accumulators wastes	22.805	2.743	1.870
Mixed waste			
Household and similar wastes	1.362.532	1.519.835	1.815.770
Mixed and undifferentiated materials	1.045.093	742.018	850.707
Mineral waste			
Mineral waste from construction and demolition	1.428.798	1.250.175	1.210.595
Other mineral wastes (W122+W123+W125)	90.748.429	91.028.374	88.491.527
Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	629.931	504.331	482.207
Sludges and liquid wastes from waste treatment	72.904	111.311	181.966
Sorting residues	662.350	865.527	506.102
Soils	16.378.694	21.789.333	13.365.262
Total	**121.503.998**	**126.770.566**	**114.912.256**

Table A8 Finnish CRM enriched waste streams

Finland: Elements in waste

	Total	WEEE	Batterie	Ashes	Cars & Tires	Tailings	Iron/ Steel	Non-Ferrous Ind.	Other
Antimon	1.343	30	383	157	24	87	283	354	24
Arsen	17.694	3	10	152	20	15.500	242	1.239	529
Barium	22.090	60	1	1.498	228	19.310	420	507	65
Beryllium	46	0	0	1	0	42	2	-	0
Bor	505	37	3	256	33	19	155	-	1
LREE	5.545	85	25	195	49	2.421	282	45	2.443
HREE	1.482	12	1	45	19	969	216	46	172
PGM	35	3	-	1	13	-	-	18	0
Fluor	9.701	17	1	185	32	-	9.385	70	12
Fosfor	36.346	12	18	10.116	140	21.828	2.028	80	2.125
Gallium	106	2	-	12	1	-	62	28	1
Germanium	12	0	-	1	0	-	1	9	1
Hafnium	15	1	-	4	4	-	5	0	0
Kobber	53.006	5.190	205	1.326	8.318	34.479	806	2.453	228
Kobolt	6.704	29	257	57	32	5.895	92	327	16
Litium	719	4	65	60	92	262	31	200	4
Mangan	91.514	12	297	4.736	765	64.934	18.933	1.817	22
Nikkel	50.402	69	296	161	89	41.714	4.533	3.523	18
Niob	308	0	0	12	12	13	261	-	9

Scandium	466	0	0	25	0	432	6	2	1
Strontium	11.485	28	0	560	201	5.137	338	236	4.984
Tantal	95	9	-	3	27	13	18	22	3
Vanadium	10.826	1	0	87	4	5.628	5.028	62	15
Vismut	352	5	1	40	1	16	211	73	7
Wolfram	359	4	0	25	40	172	115	3	2

CRM-waste streams in Iceland

Table A9 Icelandic overall waste streams, Source: Eurostat

Iceland

EU waste category	2016	2018	2020
Industrial waste			
Acid, alkaline or saline wastes	59	34	19
Chemical wastes	117.901	120.936	119.689
Industrial effluent sludges	147	370	252
Combustion wastes	9.426	8.145	8.286
Spent solvents	75	82	93
Used oils	2.741	3.029	4.561
Biological waste			
Animal and mixed food waste	23.769	30.114	30.133
Animal faeces, urine and manure	715	696	1.326
Vegetal wastes	10.707	9.647	10.589

Common sludges	4.427	4.034	4.233
Health care and biological wastes	348	326	412
Metallic waste			
Metal wastes, ferrous	24.418	50.087	67.613
Metal wastes, mixed ferrous and non-ferrous	32.541	25.966	7.217
Metal wastes, non-ferrous	1.485	1.783	4.454
Non-metallic sorted materials			
Glass wastes	7.208	7.729	6.443
Plastic wastes	7.975	10.966	7.974
Rubber wastes	6.305	9.821	5.542
Textile wastes	0	1	0
Wood wastes	25.157	27.179	48.867
WEEE and vehicles			
Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	4.105	4.982	4.863
Discarded vehicles	8.536	15.692	15.882
Batteries and accumulators wastes	1.267	1.696	1.685
Mixed waste			
Household and similar wastes	127.765	147.003	117.153
Mixed and undifferentiated materials	32.432	24.678	27.568
Mineral waste			
Mineral waste from construction and demolition	475.368	608.968	412.987
Other mineral wastes (W122+W123+W125)	24.697	10.639	6.954

Waste from waste treatment			
Mineral wastes from waste treatment and stabilised wastes	0	0	0
Sludges and liquid wastes from waste treatment	0	87	0
Sorting residues	7.893	13.541	10.349
Soils	75.172	120.176	112.443
Total	**1.059.426**	**1.279.883**	**1.050.554**

Table A10 Iceland and territories CRM enriched waste streams

Iceland & territories: Elements in waste

	Total	WEEE	Batteries	Ashes	Cars & Tires	Tailings	Iron/ Steel	Non-Ferrous Ind.	Other
Antimon	189	2	36	131	0	-	-	19	1
Arsen	20	0	1	1	0	-	-	16	2
Barium	340	4	0	10	2	26	-	90	209
Beryllium	1	0	0	0	0	-	-	1	0
Bor	120	2	0	2	1	-	-	1	114
LREE	15	9	2	1	0	2	-	1	0
HREE	2	1	0	0	0	-	-	1	0
PGM	0	0	-	0	0	-	-	0	0
Fluor	8.406	1	0	3	-	-	-	8.359	44
Fosfor	98	1	2	54	1	-	-	41	0
Gallium	10	0	-	0	0	3	-	7	0
Germanium	0	0	-	0	0	-	-	0	0

Hafnium	0	0	-	0	0	-	-	0	0
Kobber	903	525	19	20	1	1	-	89	247
Kobolt	36	3	24	0	1	1	-	7	0
Litium	293	0	6	1	0	-	-	69	217
Mangan	112	1	28	14	0	-	-	32	37
Nikkel	82	5	28	1	0	1	-	45	3
Niob	2	0	0	0	0	2	-	0	0
Scandium	0	0	0	0	-	-	-	0	0
Strontium	57	2	0	3	0	38	-	12	1
Tantal	1	1	-	0	0	-	-	0	0
Vanadium	70	0	0	0	0	7	-	62	0
Vismut	1	0	0	0	0	-	-	1	0
Wolfram	1	0	0	0	0	-	-	0	0

Appendix 3 Waste streams with direct recycling potential

While the former sections of this chapter have dealt with waste streams at an overall level that often include several sub streams where only some can be expected to be enriched with CRMs, this next section highlights some selected waste streams that are considered to have direct CRM-recycling potential.

Mineral waste streams

Tailings

Tailings are the remains from the mineral industry, after the target minerals have been extracted. The tailings are by far the biggest volume of waste in the Nordics, with more than 100 million tons even when applying a strict definition of tailings.

Tailings will mineralogically and chemically differ greatly from case to case and even over time. It will also vary from highly toxic and problematic to inert and benign. Due to the massive amounts, the tailings will contain half or more of all CRMs ending up in waste in the Nordic. The category contains both the most interesting fractions, such as the REE-tailings from Kiruna, Sweden, but also several uninteresting fractions that never can be used for anything.

In the production overall statistics only processed tailings from certain mines. All waste rock is excluded, as is fines and several other fractions from industrial minerals mines and quarries. Downstream processing wastes are found under slags etc. Hence, the 100 million ton of tailings include only material that have been crushed and separated by basic mineral processing technologies.

Sweden and Finland have the dominating mining industries in the Nordics, generating 55 and 40 million tons of tailings each. Norway has a much smaller industry generating appr 5 million tons, as the Norwegian political consensus for the last +50 years has been to develop and promote the oil and gas industry, while mining of metals and minerals has had a low priority and political support.

In Svalbard, the last coal mine is about to close. There have been no legacy mines in any of these autonomous and semiautonomous areas that have generated tailings.

Denmark has mining of large volumes of materials, but only of industrial minerals which are used almost in entirety – such as limestone. Hence, no tailings are produced of importance.

There are no mines or quarries extracting metals or industrial minerals in Iceland, only aggregates and other materials for building purposes. Hence, there are no processable tailings from mining operations. There is also no mining in the autonomous areas of Faroes and Åland.

Even if Greenland has been touted as a mining region of the future due to the receding icecap, mining activity has actually been reduced in later years. At current, only one minor mine is active, producing anorthosite. It generates limited amounts of tailings which is rather low on most metals, but is included in the statistics.[36] The ruby production that was active until some months ago had a small tailings disposal.[37] No proper tailings composition from the ruby production is found, but at least the composition of the target material could give some guidance.[38]

In the aggregated tailings statistics, we have only considered tailings from <u>operating</u> mines. Almost yearly, mining projects start, some end, and many are changed or restructured. Hence, the tonnages, composition and final waste disposal will fluctuate.

Notably, in the Nordic countries there are billions of tons of legacy tailings and waste rock dumps containing CRMs. The potential in such deposits have been pointed to in CRMA,[39] but is not evaluated in this report. Quite a lot of good work have already been done on this issue, and probably about half of historical tailings dumps with CRM potential have already been mapped. This work has been carried out with systematics and diligence in Sweden,[40][41] to some degree in Finland but not at all in Norway. An obvious task when looking for feedstock for increased production of secondary CRMs would be to make a proper inventory for all the Nordic legacy waste rock and tailings resources with volumes, grades, location, processability evaluations etc.

One legacy example would be Grängesberg in Bergslagen, Sweden. Appr. one hundred years of flotation of iron has left 10 million ton of tailings with 20% of apatite containing phosphate and REE. The company Grangex[42] is currently planning to reprocess these tailings, which would be a good preamble for the restart of the iron mine itself later on. There are also other legacy reprocessing projects under consideration on several locations, in particular in Sweden.

Producing more from existing mines by increasing extraction efficiency and reprocessing old tailings should be included in the CRM strategy for the Nordic Countries.

36. Hudson Resources inc. Environmental Impact Assessment (EIA): White Mountain Anorthosite Mining Project. 2015.
37. During the production of this report, the mine was decided to close. Refinancing and new ownership is expected.
38. Giuliani et al. Ruby Deposits: A Review and Geological Classification. Minerals 2020
39. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160, #43.
40. Rönnåsen, L. Hållbar utvinning och återvinning av metaller och mineral från sekundära resurser. SGU 2023.
41. Lewerentz et al. Hållbar utvinning och återvinning av mineral och metall från sekundära resurser. SGU 2021.
42. Bergfald Environmental Consultants assist Grangex in the P/REE reprocessing preparations.

If future work also explore the potential CRM catch by going into historical tailings dumps, fines from industrial minerals and waste rock – it is fair to assume that the potential for supply of CRMs will be greatly increased.

Rhenium is a highly strategic material that currently is not on the EU critical list. We assume this is partly due to the supplies of primary Rhenium from Poland and the established recycling from its use as catalysts and alloys. However, in a world with increasing need for defence-sensitive materials, we find it opportune to mention rhenium also in the tailings context – because it is there we mainly find it. Rhenium is produced from copper ores, or more precisely, as a byproduct of the byproduct molybdenum concentrate sometimes found in copper ores. Sweden, as a dominating copper region with several important mines, there are rhenium values. This has been mapped in the Aitik region, where the critical rhenium currently is landfilled.

Trade-offs between resource utilization and economy

In mineral processing, the extraction efficiency is always influenced by economic trade-offs. In short, if power prices or interest rates go up – extraction efficiency goes down. It is always more costly to recover the last percentage of contained valuable material than the first. Hence, all mineral value chains are sensitive to changes in the economic sentiment.

In iron processing, it is common that tailings contain 1–3% iron, while in copper it is common to leave 500–1000 ppm, in gold – the tailings will normally contain <0,2 ppm. Prices and costs determine efficiency – and remaining levels in waste.

In all operating mines, extraction efficiency could be increased, both supplying more of target minerals (some of which are CRMs) and reduce the net landfilling rate if it was economical incentivized to do so.

The most important factors to increase efficiency is the price of the minerals. If prices of copper, REEs, PGMs etc is doubled – a lot of processing is more efficient and possible and extraction efficiency goes up and landfilling volumes go down.

The second most important is the costs, mainly of power and capital. All mineral processing plants are optimised with a trade-off between extraction efficiency and costs – meaning that reduced costs of power and capital will incentivise extraction.

With reduced cost of capital for CRM-producing mines, it will for example be possible to install secondary flotation plants after the primary, if there is only one flotation step, or a tertiary unit after the second – if there are two steps already. Any extra flotation step will extract additional CRMs (typically hundreds of ppms of copper or cobalt, PGMs etc) from the process stream, but will add extra capital costs and extra OPEX.

These trade-off issues would from a CRM perspective be most important for base metals mines and their tailings, as mapped by several institutions.[43][44] But it might also be relevant for the coming Swedish and possible future Finnish REE-industry.

One possible path towards greatly increased CRM supply from wastes would be to establish a banking mandate where CRM extraction gets loans at same terms as agriculture or renewable energy gets today.

It has not been straightforward to find proper data for volumes and composition of tailings. Waste is never that highly prioritized for analysis and documentation. Some of these data might be old or unprecise (for example XRF-analysis from university students), but the amount of data should provide sufficient confidence in the overall indicative tonnage.

A special look at phosphorous

Phosphorous (P) is one of the rather dull CRMs, even if it is essential to human life. Every human need appr. 4 grams of P per day, and the use of mineral fertilizers in agriculture is necessary to provide this. In the Nordic countries, we have one phosphate mine (Yara Sillinjärvi), one possible producer of phosphate byproducts (LKAB Kiruna) and three fertilizer plants, (Yara Herøya, Yara Glomfjord and Yara Finland). The two Norwegian plants are entirely based on imported apatite, almost all from outside of the Western Hemisphere. These plants import 1 million ton of rock phosphate, with a content of 152,000 tons of P annually. This is enough fertilizer to feed 40 million people. In comparison, 154,000 tons of P is landfilled in tailings in the Nordics annually without ever having been put to good use.

Tailings from Norwegian mineral industries (as well as Swedish and Finnish) have been tested,[45] and to some extent used directly as fertilizer. Currently, the key minerals used as fertilizer, phosphorous and potash, are imported to Western Europe from Russia and Belarus. It is important then to note that the Nordics are landfilling similar or greater amounts of finely grounded rock with significant P and K levels. One of the benefits with P and K-bearing tailings is slow release and combination with pH-adjusting elements such as calcium and magnesium. This has made P/K-rich tailings accepted as fertilizer in ecological agriculture. However, as farmers have been unwilling to buy fertilizers that improve fertility of the soil over years instead of in a few days, the distribution has been discontinued and these P-rich tailings are now released to sea. If access to Russian phosphate should be restricted, or agricultural use of raw material gets similar restrictions on spreading of heavy metals and radionuclides as other industries – these slow release P/K-tailings fractions could be revitalized.

43. Lövgren et al. Immobilisation of trace metals in sulfidic mine tailings. IMWA 2011
44. Stolz, E. Release of metals and arsenic from various mine tailings by Eriophorum angustifolium. Plant Soil 2006.
45. Heim, M. Avgang fra bergindustrien brukt som steinmel i landbruk – Fakta, FoU-muligheter og –behov. NMBU 2006.

A special look at REE

The REE content of tailings currently landfilled from the main sources in Scandinavia (Yara Sillinjärvi,[46] Terrafame,[47] LKAB Kiruna,[48][49] Sibelco Stjernøya)[50] would be sufficient to build 2 million full size BEV – if extracted. Even with only 50% extraction efficiency, this represents more than the annual sales of all cars, buses and other rolling modes of transport in the Nordics.

Figure A1 PG stacks in Siilinjärvi has a growing inventory of CRMs.
Photo Yara.

Phosphogypsum from the Siilinjärvi plant, REE-extraction.[51]

This and other research have shown that it is realistic to recover 50–85% of REE-content of phosphogypsum, depending on material specific and cost-related issues.[52] At low recovery rates of ~50, expected costs could be comparable and possibly even competitive with mining costs in low-cost markets such as South-East Asia.

46. Turunen et al. Factors Contr. the Migr. of Tailings-Derived As: A Case Study at the Yara Siilinjärvi Site. Mine W. Env. 2016.
47. www.terrafame.com/newsroom/media-releases/terrafame-is-preparing-laboratory-scale-extraction-trial-of-rare-earth-elements-and-uranium.html?p389=13
48. Peelman et al. Hydrometallurgical Recovery of REEs from Mine Tailings and WEEE. J.ofSust. Metallurgy 2018.
49. Mählitz et al. Ch. the Urban Mine—Challenges of Simplified Chemical Anal. of Anthropogenic Mineral Residues. Res. 2019.
50. Haugene, M. Mob. av Ba fra et vekstmedium tilsatt apatitt-biotitt-karbonatittsteinmel ved kolonnef. M.Th. NMBU 2014.
51. Virolainen, S. Recovering REEs from PG using a RIL process: Sel. of resin, leaching agent, and eluent. Hydromet. 2019.
52. Xie et al. A Critical Review of the Enhanced Recovery of Rare Earth Elements from Phosphogypsum. Metallurgy 2023.

The high recovery technologies will generally be significantly more costly per tonne of reclaimed REE compared to the low-cost technologies, but not necessarily more costly than extraction from other wastes.

REE-content of Siilinjärvi has been properly measured in ore, tailings and Phosphogypsum waste – as well as apatite concentrate.[53] Tailings volumes are a significant future source of materials.

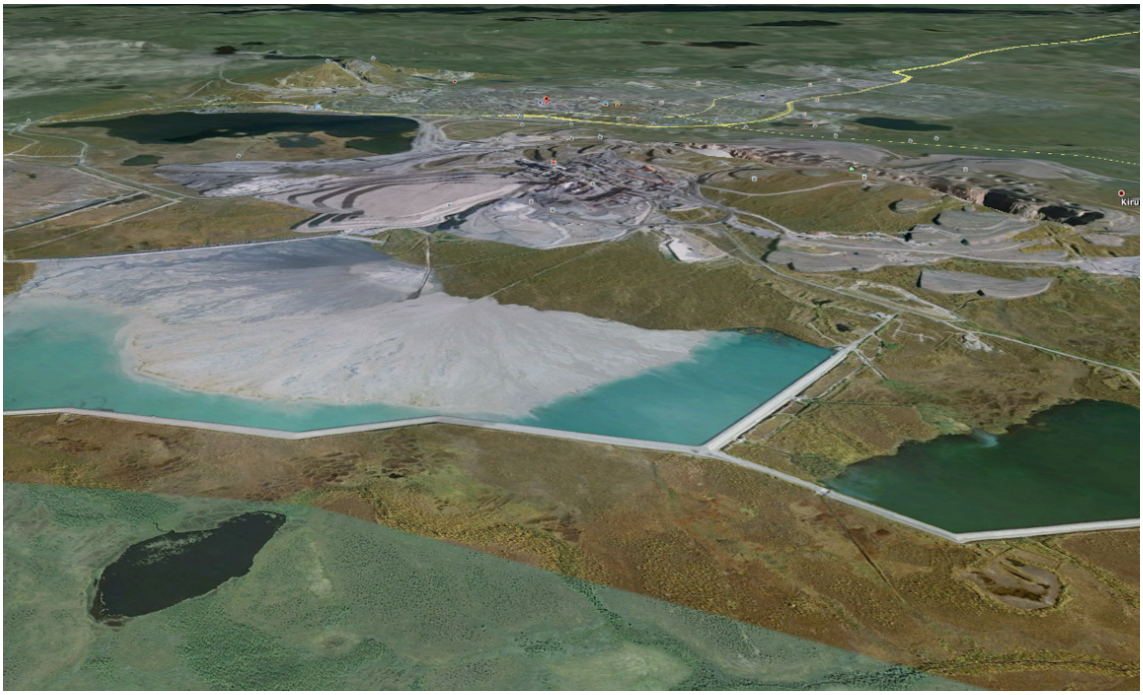


Figure A2 LKAB is investing billions in producing CRMs from its own waste.[54] Photo LKAB.

The most important REE-supplier in the years to come is however LKAB. The highly profitable magnetite production is dented with a small contamination of apatites, and these apatites contain some REEs. Grades are low,[55] but the huge volumes[56] of magnetite production, and the need to remove apatite to make the magnetite useable has provided a perfect match. LKAB has for many years worked on different possibilities for processing[57] the apatite material that is currently a waste product. The current plan is to refine the flotation concentrate and crack this to make both a phosphate product and a suitable REE concentrate. The REE-concentrate will then be transported to Norway, to the REEtec[58] separation plant for refining. It is expected that LKAB in a very few years will become the most important supplier of the most critical raw materials to the European markets from what currently is a flotation waste.[59]

53. Yang et al. Rare Earth Occurrences in Streams of Processing a Phosphate Ore. Minerals 2019
54. Sun et al. Pyrometall. Treatment of Apatite Conc. with the objective of REE Extraction. J. Sustain. Metall 2017.
55. Karlkvist, Tommy. Selectivity in Calcium Mineral Flotation - An analysis of novel and existing approaches. PhD Thesis. 2017
56. www.milav.se/wp-content/uploads/2022/12/Presentation5dec2022.pdf
57. Friberg, V.K. Tolkning av kemiska analysresultat kopplade till LKAB: s framställning av apatitkoncentrat. Luleå University.
58. www.reetec.no/
59. Chipakwe et al. Nanobubble-Assisted Flotation of Apatite Tailings: Insights on Beneficiation Options. ACS Omega 2021.

Consideration about the transition metals

The amounts of key metals for the Green Shift ending up in tailings is huge. For example, regarding transition metal CRMs like copper (5000t), cobalt (7000t), nickel (55,000t) and manganese (205,000t) are all landfilled annually in the Nordics. Each of these volumes would have mandated an own significant mining operation – if it was concentrated in one particular mineral waste stream. Unfortunately, these volumes are distributed all over the 100 million tons of tailings, in different minerals and concentrations. However, significant volumes of the transition metal CRMs currently ending in the tailings waste may be extracted if framework conditions improve.

One example could be to change the structure of the mineral royalty. Almost all mineral extraction is covered by a royalty, or mining rights fee, to the Government – partly to finance the Mineral directorates. These are fully tax-deductible costs, and they are often not connected to the extraction efficiency. Sometimes these fees are only connected to the right to extract – not the extraction itself.

These fees could be quadrupled by ton, and then turned around from extraction fees to landfill fees, such that the mineral processing companies would be incentivized to recover the CRMs. Such a change in fee structure would make it sensible for companies to install an extra flotation step, increase processing times, increase grinding etc – as they have the benefit of both extra income and reduced taxes with increased recovery and efficiency.

Alum Shale

Alum shale is common in the Scandinavian countries,[60] and has a long history of commercial use in Norway, Sweden, Denmark and Finland. The shales have been in use in the period 1650–1970, to produce dyes, pigments and critical metals by both artisanal and industrial plants.

Sweden has historically had the largest operations, with high-tech extraction plants operating for years. There have even been recent plans for restart of operations.

Denmark and Finland have less alum shales, but some. It is also found in Åland, but not in Iceland or the other autonomous regions.

Alum shale is rich in both toxic and critical elements, and is generated as a waste from building of infrastructure.

Alum shale contain all the CRMs,[61] generally in grades that are lower than what is currently considered commercial ores.

60. Anderson et al. The Scandinavian Alumshales. SGU 1985
61. Lecomte et al. U min. in the alum sh. form., Sweden: Ev. of a U-rich marine black sh. from sed. to metamorph. OGR 2017.

The important difference between commercial CRM ores and alum shales is that while commercial metallic ores have financial and environmental mining cost the alum shale has additional disposal cost due to its mechanical and chemical properties.

Today, alum shales are a waste problem connected to newbuilds of roads and tunnels etc as well as the restrictions on certain urban areas from development due to legacy wastes from prior alum shale processing.

In all, there are several hundreds of millions of tons of legacy alum shale landfilled in the Nordics, as well as at least half a million ton of alum shale ash from burning of the shales. Indeed, in downtown Oslo there are lakes and regions named from this activity (Alunsjøen and Alna) as well as a road named after the residue from alum shale burning – Rødfyllgaten.

Tons

There are no commercial production of alum products currently. However, every year around 250–300,000 tons of alum shale[62] is extracted due to Nordic infrastructure works. Based on certain criteria, this alum shale is transported to dedicated landfills at considerable cost. When dug out and then landfilled, chemical reactions with oxidation of sulphides and carbon are initiated increasing heat and solubility of the metals, hence the dedicated landfills for alum shale are at risk of leaking dissolved metals, and have specific and strict operations requirements.

The volumes of alum shale landfilled is varying from year-to-year dependent of which projects that are carried out in different regions, which makes proper waste treatment difficult.

In Norway, for the last years around 100,000 tons have been dug out. The excavation of the new government HQ in Oslo with 175,000 tons and a single large road project in E6 Expansion with above 100,000 tons have dwarfed the prior smaller[63] regular[64][65] deliveries of 10–20,000 tons from ongoing road maintenance works. Based on the aggregated reference projects, 150,000 tons has been selected as an annual long-term estimation for Norwegian alum shale generation. Sweden has over time processed larger volumes, but we have found less recent references to compare with. Sweden is in all aspects a unique region regarding alum shales, as these resources are covering 1% of the Swedish territory. Despite having these huge resources, Sweden has imposed particular legislation to restrict production. In the lack of firm numbers, similar volumes to Norway with 150,000 tons as an average[66] is selected as an estimate, but the real number may be significantly larger.

62. Including high-metal-concentration black shales.
63. Santos, S.H. Pot. Mob. of radion. and trace elem. in bedrock mat. and in the dep. area at a tunnel constr. Site RV4 Gran, Hadeland. M.Th.NMBU 2014.
64. Wærsted, F.M. Mob. of nat. occ. Radion. and stable elements in alum sh.: A case study of Gran, RV4, Norway. PhD 2019.
65. Wærsted, F.M. The effect of water exchange on the leaching of alum shale. Applied Geochemistry 2020.
66. Petterson, A. Spårämnen i alunskiffer, rödfyrshögar och björkträd vid Andrarums alunbruk, Skåne. Lunds University 2011.

Based on the location of the alum shales, limited extent of their alum shale areas, population densities in the areas and probable coverage, we have assumed 10,000 tons per year in Finland. Denmark might be a special case, as they in addition to land-based alum shales have had an issue with deep drilling into high activity alum zones, generating drilling mud with high uranium levels. Denmark has issues both with the material from Kattegat and on land in Bornholm.[67] We have assumed annual landfilling of 10,000 tons also for Denmark. Åland has some alum shales, but we assume that the volumes that need proper consideration is only one truckload a year. The other autonomous regions as well as Iceland is assumed to not have alum shale issues.

Figure A3
Left: Norwegian alum shale problem.[68] Narrow bands, but high overall tonnage. Photo Statens Vegvesen.
Right: Swedish alum shale processing plant,[69] currently decommissioned. Historical photo, Platåbergens Geopark.

From waste to resource

The alum shale of Scandinavia could be turned from a problematic waste issue to a relevant regional resource.

As alum shale already is inflicted with a substantial gate fee for its treatment, it could be rather interesting to see if minor adjustments to the treatment practise could stimulate the extractability of some of the CRMs, providing a long-term supply of some volumes of amongst others REEs, uranium and some base metals.

Landfilling of alum shales in Scandinavian carry costs of appr. 1000 NOK/ton, including documentation and transport costs.[70]

67. Hansen, S.F. Overordnet beskrivelse /screening af risici og farer ved indvinding af skifergas. DTU 2016.
68. Fjermestad, H. Rv. 4 på Gran, nyttiggjering av svartskifer. Statens Vegvesen 2018.
69. www.platabergensgeopark.se/wp-content/uploads/2023/01/Flygbild-over-Ranstadverket-15ACEF1D-6307-4DE1-AA9D-E980BEA6F21D.jpg
70. Personal communication with insiders in the roadbuilding and landfill industries in Norway.

The establishment of a multimetal processing plant somewhere in Scandinavia with the capacity of receiving for example 3–500,000 t of shale would both handle all volumes regularly arising with a gate fee of 200–300 MNOK as a steady income. In addition, it would be able to deplete some of the complex legacy sites which currently produces emission and groundwater issues and limit urban and logistical development. Such a plant would be able to cover a significant portion of the Nordic use of heavy REEs, such as dysprosium. In addition, a plant could supply uranium and some base metals.

While there is some experience in advanced processing of alum shales globally, some adaption would probably be needed, for example in handling radon issues. From a chemical perspective, there are substantial relevant industrial experiences in the region, for example from the Terrafame[71] and Sillamäe[72] processing plants. Access to oxygen is a key to mobilize the metals from its anoxic origin.[73]

The basic chemistry of alum shale processing is not very complicated. The shales were formed as sediments in the anoxic layers of primordial lakes. Due to the water chemistry, the metals precipitated from the water to the sediment and was enriched. When exposed to oxygen again, the sulphides are oxidized to sulphate, lowering the pH, increasing the temperature and resolubilizing much of the metals. If this can be done slowly in a controlled setting, like the black shale processing plant Terrafame in Finland, the resulting acidic water would become a PLS carrying valuable metals. While this in theory works well, there are substantial practical and regulatory issues that need to be solved.

There have been several projects for commercial, processing of alum shale in Sweden[74] and Norway[75] that has never been matured,[76] possibly due to regulatory difficulties. We have observed that the Swedish Geological Survey proposed alum shale processing[77] as a direct response to the EU CRMA work in 2022 and its earlier evaluation as possible source of REEs in Sweden. With the possibility of supplying several tons of dysprosium – this makes sense.

Technology has been tested, with different maturities, for the extraction of vanadium,[78] REE,[79] K,[80] uranium[81] etc from alum shale. Experiences from Estonia, having processed similar shales in long periods indicate extraction of key CRMs of 70–85%.[82]

71. www.terrafame.com/
72. Lippmaa, E. Estonian Graptolitic Argillites – Ancient ores or future fuels. Oil Shale 2009.
73. Wærsted, F.M. Lim. access to oxygen red. the release of harmful trace el. from submerged alum shale debris. SotTE 2023.
74. Voronin et al. Chemical weathering of lower paleozoic black shales of south Sweden. J.of Mining Inst. 2018.
75. Abreham, A.Y. Reactivity of alum and black shale in the Oslo region, Norway. M.Th. Oslo University 2007.
76. Freiberg, R. Rödfyr - En utredn. av användningsområden och hantering med fokus på ekonomi och miljö. Jönköping 2015.
77. www.sgu.se/en/mineral-resources/mines-and-environmental-impact/alum-shale/
78. Gunnarson, N. The content, ch. state and acc. of V in a drill core of Alum shale from Kinnekulle. Diss. Lund Uni. 2019.
79. Engstrøm et al. REEs in the Swedish Alum Shale Form.: A Study of Apatites in Fetsjön, Västerbotten. Uppsala Uni. 2019.
80. Hedvall et al. Producing K salts from Swedish raw material. The Swedberg (mem.vol.) 1944.
81. Beeson, R. The giant Alum Shale polymet. dep. of Jämtland, Sweden –a pot. low-cost suppl. of U for the future. IAEA 2014.
82. Maremaee et al. Metal extraction from alum shale ashes under the effect of ammonium sulphate. Oil Shale 1991.

Bench tests have indicated the Swedish alum shales as relevant feedstocks for uranium, vanadium, nickel and molybdenum and possibly also beryllium and rare earths.[83]

Possible actions to increase CRM recovery:

- Avoid imposing restrictions on alum shale of the kind established by Sweden in 2022.[84]
- Consider the establishment of a joint Nordic shale processing plant with high CRM recovery mandates, financed by gate fees and a ban on all other shale disposals.
- Expect uranium to be included on next revision of CRM list, and uranium to be a key product from an alum shale processing plant.

Waste from processing raw materials

Jarosite – the zinc residue gold mine

Zinc is a versatile and low-priced metal with many applications. Its main use in corrosion protection of steels. Zinc is also recycled to a large degree. For this report, however, it is the primary production that is of most interest, more specifically – the jarosite leach residue with high content of CRMs.

Zinc itself is not regarded as a CRM by EU, in contrast to USA, Canada, South Korea, Russia and South Africa that see it otherwise. One of the main reasons for the EU consideration was the operation of the large Tara zinc mine in Ireland, the many zinc refineries in Europe and the rather well-developed recycling industry based on EAF dusts and residues. However, in June 2023, the Tara mine was closed, and Europe is now heavily dependent on import of zinc concentrates as the remaining European zinc mines are too small to cover consumption.

The zinc sulphide concentrates mainly refined in Europe all contain a lot of contaminants. Some of these are CRMs, such as indium, germanium and gallium, but also precious metals such as gold and silver are common as contaminants. In some regions of the world, these contaminant CRM metals are extracted but not in the Nordics. Obviously, the distribution and overall content of these minor contaminants vary wildly between zinc feedstocks. The content of CRMs in jarosite residue will vary both based on feedstock, as well as the finer details of the hydrometallurgical processing technologies applied.

83. Jackson et al. Energy Independence for Europe: Uranium and Oil from the Alum Shale. 2010
84. www.regeringen.se/rattsliga-dokument/lagradsremiss/2022/02/forbud-mot-utvinning-av-kol-olja-och-naturgas-och-skarpta-regler-for-utvinning-i-alunskiffer/

At present, there are two primary zinc refineries in the Nordics, the Boliden Odda plant in Norway, and the Boliden Kokkola plant in Finland. The production technologies and waste characteristics are rather similar, given their coordinated feed supply and operations. Following from the closure of Tara mine, it is reasonable to expect a change in jarosite composition. In both cases, the plants receive recovered and recycled zinc feedstocks. The increasing use of waste electronics as feedstock in their mother company Boliden will generate a zinc byproduct with high concentrations of tin, in addition to a wide range of other CRMs. The tin and the CRMs end up in the deposited waste[85] – while the non-CRM zinc is refined.

The dominating waste from both refineries is the alkaline iron sulphate mineral Jarosite, that is produced in a volume of appr. 150,000 tons in Odda and 200,000 tons in Kokkola. The Odda plant is currently undergoing a 5 billion NOK upgrade – which will provide a doubling of both metals and waste production.

Boliden has together with the Finnish Research institution VTT developed the Jarogain process for extracting some valuable materials from the jarosite.[86] This process is a very good starting point for a drastically increased recovery of CRMs,[87] as well as reduced landfilling of waste. It is possible with matured technology to achieve high extraction rates.[88][89][90]

If proper extraction technologies for the zinc residues are implemented, it should be possible to extract both indium, germanium and gallium content from the annual waste production sufficiently to cover all Nordic needs. If the millions of tons of jarosite from earlier production is reprocessed as well – all European needs could be covered. A competitor plant in Belgium is already looking into similar extraction.[91] Also work from outside of the Nordics indicate that jarosite residues might be the easiest way of reclaiming significant volumes of indium.[92]

It has been challenging to establish realistic estimates from public sources of the current content of the jarosite sludge deposited by the Boliden plants. Estimates have been made on a combination of different Norwegian[93] and Finnish sources, as well as a list of international references.[94]

85. Bertilsson. Study of leaching behavior of tin in Zinc-clinker and Mixed Oxide. Luleå Uni. 2018
86. Kangas, P. The Jarogain Process for Metals Rec. from Jarosite and EAF Dust - Process Design and Economics. VTT 2017.
87. Rämä et al. Thermal Processing of Jarosite Leach Residue for a Safe Disposable Slag and Valuable Metals Rec. Metals 2018.
88. Karumb, E. The recovery of indium from mining wastes. M.Th. Colorado School of Mines.
89. Swain et al. Recycling of Jarosite For Recovery of Valuable Metals and its Utilisation. IJSTRE 2016.
90. Ma et al. Stat. anal. and opt.of rec. In from jarosite res. with vacuum carboth. red. by response surf. meth. GP&S 2016.
91. Rosendael et al. Selective rec. of In from iron-rich sol. using an Aliquat 336 iodide supp. ionic liquid phase (SILP). SPT 2019.
92. Janošević, Miloš. Indium Recovery from Jarosite Pb–Ag Tailings Waste (Part 1). Minerals 2023.
93. Gravdal et al. Optimalisering av sedimenteringen på jarosittfellingstrinnet. Batcheloroppgave 2022.
94. Hoeber et al. A compr. review of processing strategies for iron precipitation residues from zinc hydromet. CE&T 2021.

In the mountain caverns Boliden is operating in Odda, Norway, they are also mixing in some other wastes in the jarosite sludge, including wastes from the lead processing in Sweden. Some of the reference numbers used include these mixed wastes, gathered from documents from the Boliden group.[95]

The jarosite waste in the landfills in Kokkola and the mountain caverns in Odda should be regarded as important European CRM resources. Hence, restriction should be put on these resources. We recommend the following:

- That hazardous wastes without CRM value should not be blended into the CRM-rich fractions.
- Possible recovery technologies should be supported financially.
- Suggestions to use jarosite as material for ceramic or glass production should be restricted.

EAF Dust

When iron and steel are recycled, the feed brings with it almost all of the periodic table as either alloying elements, surface treatment elements or contaminants. These elements will either dissipate into the steel, migrate to the slag or evaporate from the furnace for later to condensate and end up in the dust that is collected in dust bags on all the Nordic steel and foundry plants.

The single most important metal in such dust is zinc (iron is ignored in this context), which is present in concentrations from 15–50%, with an overall average of 22%. As zinc is valuable (though not considered critical by EU), almost all such dust (with some notable exceptions) is sold as feedstock for zinc recovery.

The main processing step for this dust in a European context is the Waeltz kiln, where the dust is mixed with large quantities of coke together with other zinc wastes such as batteries, sludges, galvanic residues, zinc smelting crusts, zinc dross etc and volatilized in large rotary kilns. The non-zinc part of the recycled material becomes a slag, locking in all remaining metals in a hard-to-process mixed matrix, including the critical metals. Indeed, the current processing technology for such dusts immobilize the critical metals while recovering only one non-critical metal. Several technologies have been developed, tested and proposed for increased recovery from these dusts, but without any attention from regulatory authorities or interest from the commercial market.

Accurate data on composition and volumes of EAF dust in the Nordics is not publicly available. However, both the scrap iron used as feedstock in the furnaces and the EAF dust itself are today globally traded commodities. Indeed, dust is

95. Boliden. Søknad om deponering av farlig avfall i Mulen deponi 2020.

shipped back and forth between the continents. Consequently, we have been able to use a range of international references for elemental composition which has shown rather consistent compositional values. Data has been aggregated from Brazil,[96][97][98][99] Thailand,[100] Poland,[101] Mexico,[102] Serbia,[103] Malaysia,[104] Turkey,[105] Japan,[106] South Africa,[107] Spain,[108] Netherlands,[109] USA,[110] Kina,[111] Belarus,[112] Finland,[113][114] Egypt.[115]

As for volumes, we have looked at the Norwegian numbers of appr. 10,000 tons in a normal year and extrapolated a production of 50,000 tons for the Nordic. However, the global production of such dusts is estimated at 8 million ton,[116] which should indicate a production in the Nordics of 143.200 tons. As the Nordics have a significant steel industry, including both blast furnaces and several EAFs, we have used this global estimate as a basis for the calculations, while adapted the distribution amongst the Nordic countries according to the figures we have available.

The Norwegian situation could be regarded as rather typical for most of the Nordic region. In Norway, there is one major EAF dust producer in the Celsa plant in Mo i Rana with an annual production of 8–10,000 tons. Historically, this dust has partly been put into local mountain cavern, recycled at the Høyanger EAF recycling plant [117] or exported. In addition, there are 10 smaller plants; the foundries such as Jøtul, Ulefos, Hamjern etc that each generate some tens to low hundreds of tons of dust per year. These smaller plants will often end up delivering the dust as hazardous waste – landfilling the material instead of using it as CRM feedstock.

As we understand it, Boliden receives some EAF dust for zinc recycling at its plant in Skellefteå REF. In addition, there is a plant in Norway, currently idled, that also could be active in this market.

96. Silva et al. Preparation of glaze using EAF dust as raw material. J. of Materials Res. and Tech. 2019.
97. Lenz et al. Lead and zinc selective precipitation from leach EAF solutions. Revista Matéria 2007.
98. Soares et al. EAF Dust Recycled in 7075 Aluminum Alloy Composites Fabricated by SPS. Materials 2022.
99. Metz et al. Influence of electric arc furnace dust and lime kiln waste in Portland cement hydration. ANTAC 2020.
100. Metz et al. Influence of electric arc furnace dust and lime kiln waste in Portland cement hydration. ANTAC 2020.
101. Lis et al. Determination of the chemical composition of the dusts from EAF. Metals 2016.
102. Leon et al. Treatment of Haz. Waste by Carbon Dioxide Capture from an Electric Arc Furnace. ISIJ Int. 2015.
103. Trifunović et al. Investigation of hazardous waste A case study of EAF dust characterization. Hem. Ind. 2022.
104. Lee et al. A comb. hydro-pyromet. process for zinc oxide and iron oxide extr. from EAFD waste. ISGST 2021
105. Morcali et al. Carboth. red. of EAFD and Calc. of Waelz oxide by semi-Pilot scale rotary furnace. J.M.M. 2012
106. Sasamoto et al. EAF dust recycling technology in Japan. The 6th Int Symp on East Asisan Res. Rec. Tech. 2001.
107. Teimouri et al. A New Hydromet. Proc. for Metal Extraction from EAF Dust Using Ionic Liquids Materials 2022.
108. Lopez et al. Enhancement of Electric Arc Furnace Dust by Recycling to EAF. J.of Env. Engineering 2002.
109. Peters. A.G.A.. Zinc vapourisation from sludge wastes under thermal processing conditions. M.thesis 2019.
110. Holloway et al. Min. Transform. in Altasteel EAFD roasted with Na2CO3 and seco. Ferrite-Forming Additives.
111. Ma et al. Kinetic Analysis of Rec. Zinc from EAF Dust by Vacuum Carbothermic Red. at 20 Pa. Minerals 2022.
112. Matsukevich et al. Direct reduced iron and zinc recovery from EAFD. J. of Ch.Tech. and Biotechnology 2022.
113. Karppinen et al. Hydromet. of Sn and other imp. present in ind. Zn bearing Solutions. Aalto Uni., M.Th. 2020.
114. Stefanova et al. Alkaline leaching of iron and steelmaking dust. Aalto University Research Report 2012.
115. Galal et al. Synthesis of nanosized nickel zinc ferrite using EAF dust and ferrous pickle liquor. Sc. Rep. 2021.
116. Frilund et al. Steel Manufacturing EAF Dust as a Pot. Adsorbent for H_2S Removal. Energy and Fuels 2022.
117. The recycling plant in Høyanger was put on care and maintenance by owner Nyrstar/Trafigura in 2020 due to a decision to start exporting of hazardous waste out of Europe for landfilling.

Possible recommendations for this material would be:

- Mandate all generation of EAF dust with recoverable metal concentration above a certain threshold to recycling instead of landfill.
- Ban export of EAF dusts to low quality recycling such as Waeltz kilns.
- Mandate annual full spectrum analysis of elements content for all furnaces generating EAF dust.

Steel slags

The Nordic countries have a huge steel industry, with historic roots in the high-quality iron ores in Sweden, Norway and Finland. The industry consists of the iron ore mines, the blast furnaces, the EAF recycling furnaces, the converters and processors, the alloy smelters and the foundries. In this chapter, we will focus on the smelters, and the slags they are producing. Wastes from the mines are in the tailings chapter. Ferroalloys slags are included in the overall numbers.

Steel is produced in large blast furnaces from iron ore with the main energy coming from carbon such as coke. This is an industry hard pressed by climate and energy restrictions and many changes will come in the years ahead. Despite this, contaminants, slag and wastes will be an issue also in the future.

Today, when operating the traditional blast furnaces, contaminants such as sulphur and phosphorous is lifted out of the smelt by addition of limestone and other materials, generating huge amounts of slags. The cleaner the steel needs to be – the more slag is formed. In general, the slags from blast furnaces (BF) are dominated by the calcium from the added limestone as well as the silica that follows most iron ores. But almost all the rest of the periodic table is also found, sometimes due to specific contaminants in the ore, but also from the coke and contaminants in the additives. Most blast furnaces also add some scrap metal into their process to regulate reactivity and reaction temperature.

Today, most of the blast furnace slags are used as either clinker feedstock or cement replacement, utilizing the burnt limestone/silica coefficient, which provides a positive greenhouse gas footprint. However, when using the slag as cement – all CRMs in the slags are lost for recycling forever.

In the Nordics, there has been a development away from blast furnaces based on iron ore and coke – towards increasing use of scrap metal. These recycling operations based on Electric Arc Furnaces (EAF) varies in size from a million ton a year large operations to craftmanship sized of a few tons a year for niche products. When using scrap metal, all kind of contaminants are introduced into the furnace. Some comes as alloying elements in the steel, some come from surface treatment (such as cadmiated or zinced steel components), from pigments in paints or lacquers or just because its mechanically attached to the scrap iron components by glues, welding or screws.

When crude steel is made, it is mostly refined in a ladle. All of these processes; primary iron and steel, secondary iron and steel and ladle produce slags with different volumes and composition. In addition, there is added alloys to make the end product. Many of these alloys are also produced in the Nordics, for example 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.[118][119] 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,[120] in agriculture[121] or landfilled. As an example, Höganäs in Sweden has developed a fertilizer product[122] from their steel slag – while in the future it might be a CRM source.

As the focus of this report is to investigate possible CRM supplies and their recycling, we have not compared benefits of utilizing slags as aggregates or clinker replacement, we have only looked into the possible CRM content.

As the Nordic steel industry plants are highly diverse, both regarding feedstocks, processes, product and slag composition, it has been necessary to make individual slag composition estimate for all major plants and then aggregate together for the sector. A combination of reports for individual plants combined with an average level for all plants have been used for this purpose. We have amongst others used data from Uddeholm,[123] Sandvik and Outokumpu Avesta slag,[124] BF-slag from Luleå,[125][126] other slags from Luleå,[127] EAF-slags from Ovako Hofors,[128] AOD-slag from Avesta[129][130] and a special report on the recycling of slag crusts in furnaces in Sweden to improve resource utilization.[131]

118. Engstrøm, F. Mineralogical Influence on Leaching Behaviour of Steelmaking Slags. PhD thesis 2010, Luleå Uni.
119. 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
120. Lidelöw et al. Evaluation of leaching from four recycled materials used in full-scale road constructions.
121. 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.
122. Galyas, Eva. Ass. the suitability of using the byproduct Petrit-E from steel prod. as agric.fertilizer. MTh. 2021, Halmstad U.
123. Andreas et al. Rekommendationer för användning av slagg i deponikonstruktioner. Jernkontorets Forskning D843 2012.
124. De Colle et al. St. of the diss. of SS slag min.in diff. acid env. to prom. their use for the tr. of acidic wastewater. Ap.Sc. 2021
125. Larsson et al. Vanadium bioavailability in soils amended with blast furnace slag. J. of Hazardous Materials 2015
126. Hedstrøm et al. Methodological Aspects of Using BF Slag for Wastewater Phosphorus Removal. J. Env. Eng. 2006
127. Lundkvist, K. A Pr. Int. Appr. to Ass. Poss. for Impr. Mat. Eff. in N. ore-based Iron- and Steelmaking Syst. Luleå UniTh.2019.
128. Strandkvist, I. Minimisation of Cr Leaching from Low-Alloy EAF Slag by Mineral Modifications. PhD Thesis Luleå Uni. 2020.
129. Yang et al. Treatments of AOD Slag to Produce Aggregates for Road Construction. AISTech 2006 Proceedings
130. Dugu, A. The reuse of AOD-slag in electrical arc furnace. M.Thesis Luleå University 2015.
131. Salguedo, R.T. Återanvändande av skärslagg som råmaterial i ljusbågsugnen. Luleå University 2020.

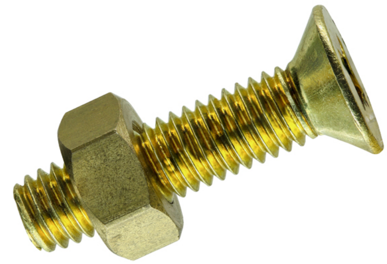


Figure A4
Left: NIB magnet fragment found on shredded steel part, a feedstock for a small iron foundry. Photo Daul et al.
Right: a brass bolt. If connected to a steel component, it will contaminate a huge chunk of recycled steel. Photo Adobe Stock.

There are almost no published articles or reports regarding the chemical composition of slags from the Celsa plant in Norway. Equally, there are very few references regarding the foundries in any of the countries. Hence, for these plants' values, average EAF slag composition has been used.

We have however been able to locate several interesting references regarding Finnish EAF slags[132][133][134][135] including reports on BF slag contain REEs[136] as well as base metals.[137]

Finland is currently of particular interest due to its vanadium project. Many iron ores have a naturally high vanadium content. The CRM vanadium is used in high strength steel alloy. When operating the furnaces, vanadium tends to be enriched in the slag, but are currently lost in existing processes.

Substantial effort has been put into utilizing this resource more efficiently.[138] Hundreds of thousands of tons of slags containing percentages of vanadium could become the feedstock of a new vanadium alloy plant, if the financing is achieved. The timing for such a recovery plant is almost perfect. Globally, the BRICS countries have 100% of the primary vanadium supply, according to the latest USGS intelligence report.[139] This project is now sponsored by the European Investment Bank (EIB).[140] If established, the Nordic countries need to make sure that it is protected against undue market manipulation by the BRICS countries, and properly supplied with relevant feedstocks from legacy slag dumps etc.

132. Tossavainen et al. Characteristics of steel slag under different cooling conditions. Waste Management 2007.
133. Eloneva et al. Co-util. of CO2 and steelmaking slags for production of pure CaCO3 legislative issues. J. of Cl. Prod. 2010.
134. Teir, S. Fixation of CO_2 by producing carbonates from minerals and steelmaking slags. PhDTh. Helsinki Uni. 2008
135. Kekkonen et al. Active tundish metallurgy. EU Report 25875 2013.
136. Omran et al. Effect of Blast Furnace Sludge Characteristics on Suitable Recycling Process Determining. JMMCE 2017.
137. Walterson, E. Chromium, Nickel and Molybdenum in Society and the Environment.
138. Attah, M. V re. from steel conv. slag utilised as an oxygen carrier in oxygen carrier aided combustion. JoCl.Prod. 2021.
139. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-vanadium.pdf
140. www.eib.org/en/projects/pipelines/all/20220153

Figure A5
Top: Stavanger Staal, Norway, manganese steel recycling rescued from closure. Photo Tor Inge Jøssang.
Bottom: Neometals, Finland, vanadium steel recycling hopefully coming. Photo Neometals.

We would also like to highlight the Stavanger Staal plant in Norway. This plant was about to close down, but has been saved by local investors and converted to a niche recycling plant only casting high manganese steel components (>20% Mn steels). In a circular economy, more niche plants such as this will be expected.

To make sure that we have a sufficiently relevant statistical basis, and that all elements are covered, we have also included an international average based on all the Nordic reports combined with reports from Romania,[141] India,[142] Belgium,[143] Poland,[144] Germany,[145] Korea,[146] Hungary[147] and Brazil.[148] This is basically to include minor CRM elements not analysed in all the plant-specific reports.

Magnets from WEEE and shredder residues are difficult to sort out.[149] When partly liberated from WEEE and in shredders, magnets will naturally cling to magnetic iron, and eventually follow the iron to secondary steel plants. Some of the magnet REEs will dissipate into the iron, while significant parts are also transported into the slag.[150]

The Nordic steel industry have several byproduct streams (dust, slag, sludge, etc.) with possible high metal and CRM values. Several of them, including materials with high zinc concentrations are included in the lists, as more profitable metals such as zinc might be important also to industrialize extraction of minor CRMs.

There are many SME cast houses in the Nordic countries generating waste such as casting sand, forming sand, filter dust, slags etc. Combined, the volume of this waste is in the region of 500,000 tons. Most of this is silica sand of little or no interest as CRM resource. Hence, these processes have not been looked into for this report.

However, some of the steel plants in the Nordic Countries use olivine as an input material; partly as a slag former and partly as casting sand – as the temperature tolerance of olivine is very high. As far as we know, this olivine mainly comes from the Sibelco Åheim resource in Western Norway. This olivine typically contains 3–4000 ppm nickel, 3–400 ppm cobalt and 2–500 ppm REEs in addition to several other CRMs.

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141. Ene et al. Ch. of met. slags using low-level gamma-ray spectrometry and neutron activation anal. Rom. J. of Physics 2011
142. Chand et al. An Overview of Use of Linz-Donawitz (LD) Steel Slag in Agriculture. Current World Environment 2015.
143. Quaghebeur et al. Acc. Carbonation of Steel Slag Compacts: Dev. of High-Strength Construction Mat. Fr.in En. Res. 2015.
144. Baron et al. Determination of REE in power plant wastes. Mining Machines 2020.
145. Daul et al. Magnet Associated Rare Earths in Steel Mill Slag. World of Metallurgy - ERZMETALL · September 2017
146. Hong et al. Metal rec. from iron slag via pH swing-assisted carbon min. with various org. ligands. J. of CO2 util. 2023.
147. Varga et al. On the Aqueous Rec. of Zinc from Dust and Slags of the Iron and Steel Prod. Tech. Int J Met. Mater Eng 2016.
148. Moreira et al. Characterization of steel slag by SEM-EDS, XRD, and INAA. Brazilian Journdal of Radiation Sciences 2021.
149. Kim et al. Recovery of scandium and neodymium from BF slag using acid baking–water leaching. RSC Advances 2020.
150. Bandara et al. Closing the lifecycle of RE Magnets: Discovery of Nd in slag from Steel Mills. Energy Tech 2015

Non-Ferrous industries

The Nordic countries have substantial non-ferrous industries with plants producing primary and secondary aluminium, zinc, copper and nickel.

A description of the CRM-potential in the wastes coming from the aluminium sector is given in the following paragraphs.

Norway and Finland have substantial capacity for refining of nickel, and supply some of the most important high-quality nickel to amongst others the battery market. Nickel slag from the smelter in Harjavalta in Finland may be of special interest due to waste streams with CRM-recovery potential.[151] These refineries are mainly in the later end of the value chain, so waste values are moderate, but included in the NFI numbers. Both nickel refineries have hydrometallurgical precipitation sludges with relevant levels of CRMs.[152]

Norway and Finland have substantial capacity in refining of zinc, this is described below in the jarosite-chapter, and the CRM-potential included in the NFI numbers.

Sweden and Finland have substantial capacity in copper refining with the two large Boliden plants in Rönnskär in Åland and Harjavalta in Finland, while Norway has a relevant refining plant in Kristiansand. Copper slag from Harjavalta is the biggest source of copper to landfill in Finland and could potentially be a significant supplier of copper to Finland if better processed.[153]

Aluminium

Aluminium has shown a steady growth as a construction material over the last 100 years, taking a firm position as the second largest metal in tonnage – despite being a lightweight metal.

Currently, the global primary production of aluminium is about 70 million tons, and with current level of recycling, an additional 30 million tons is taken back into circulation, providing a total market of 100 million tons per year.

While aluminium recently was classified as a CRM itself, the focus on this report has been more on the losses and possible recycling of the minor CRMs often associated with aluminium.

In our statistics, we have included CRM issues from several stages of the aluminium value chain.

151. Xiao, Y. Leaching behaviour of valuable metals from nickel smelter slag. Aalto University, Master Thesis 2022.
152. Godtland et al. Overview of the Norwegian metallurgical industry Part 3: Waste and by-products. NTNU 2020.
153. Kaksonen et al. Bioleaching and recovery of metals from final slag waste of the Cu smelting industry. Min. Eng. 2011.

Waste with high content of CRM from the aluminium sector comes in roughly three fractions;

1. Dross and dust from primary aluminium with content of natural contaminants from the alumina and carbon.
2. Dross and dust from secondary aluminium with content of alloying elements, surface treatment materials, fixed and glued components as well as treatment salts.
3. Spent pot liner from primary aluminium production.

There are also other waste fractions, such as anode butts, but the main focus of this report is on these three larger fractions. Limited information about chemical composition of these waste streams is available. While some references from Nordic aluminium industry have been identified, the calculation of CRMs in these waste streams have therefore also been supplemented with analysis from aluminium smelter waste outside of the Nordics.

Primary aluminium and its wastes

All primary aluminium comes from bauxite today, and many bauxite resources also contain CRMs.

It is well known that gallium is supplied entirely from recovery of upstream waste product from bauxite processing. But even germanium, indium, scandium and rare earths are common in bauxites.

To some degree these CRM metals follow the aluminium oxide feedstock to the Nordic primary aluminium smelters in Norway, Sweden and Iceland, where they either dissipate into the aluminium metal as a contaminant (most aluminium sold from the Nordics have a 99,5% purity) or end up in wastes from the smelters. The content of these CRMs in the primary waste fractions are included in our statistics. There are also other waste fractions from this sector with lower CRM content that is not included on this list.

For all practical purposes, all aluminium sold from the primary smelters, and all aluminium components imported to the Nordic countries are alloyed. Some of these alloys are also CRMs, such as manganese, titanium and REEs.

Secondary aluminium and its wastes

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. Aluminium scrap contains significant amounts of other chemical elements and need a lot of treatment before it may be used again. When aluminium from shredded cars with iron and copper beaten into it or old beer cans with cigarette buts and colourful lacquers on it is put into a smelter, it is far from a high-quality alloy. Salt is added, normally 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 are key to succeed in aluminium recycling.

This dross comes during the melting and is made by a mix of salts and oxides that generates on the top of the melt and is 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 rich in many CRMs.[154][155][156][157][158][159][160] It should be noted that if society wants to go in direction of a more circular economy with increased recycling of aluminium, there will be several technical constraints and bottlenecks that need to be solved as many of the easy to operate recycling solutions and material streams are already industrialized.

SPL – Spent Pot Liner

The cathode of a standard primary aluminium electrolysis cell is a thick carbon cladding isolated with refractory bricks from the surroundings. These cathodes become saturated with fluorides and several metals that do not easily dissipate into aluminium or evaporate. Hence, the SPL functions as an enrichment point for certain elements in low concentrations in the feedstock.

Currently, SPL is registered as a hazardous waste all over the world and strict and costly treatment is needed.[161][162] Some of the tonnage is registered as recycled, but that means its addition to steel blast furnaces or other smelters as a carbon source. There is no recycling of the inorganic materials in SPL in any country today. This is of particular concern regarding the fluoride, as the concentration in SPL is very high, and the supply situation is of concern.

Aluminium alloys and the CRM dissipation problem

Both the success and challenges of aluminium rests on alloying. For all practical purposes, all aluminium put on the market is alloyed. Most common is standard alloys with silicon and magnesium. These are common and lightweight metals that for many alloys have a generous window of composition, i.e. meaning that if silicon is cheaper than aluminium, a little more is added and vice versa.

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154. Lucheva et al. Non-waste Aluminum Dross Recycling. J. of the University of Chemical Technology and Metallurgy. 2005.
155. Afolabi et al. Compr. strength behaviours of lagoon-water cured cement-aluminum dross concrete. Kufa J. of Eng. 2021
156. Sedo, Jan. Processing method and dross dust fractions properties in the Confal Inc. European Scientific Journal May 2015
157. Yang et al. Investigation of leaching kinetics of alu. extraction from sec. Alu. dross with use of HCl. Hydrometallurgy 2019.
158. Singh et al. Quantitative determination of metals in waste aluminum dross. IOSR JAC 2018.
159. Lin et al. Recycling of aluminum dross for producing calcinated alumina by microwave plasma. Sust. Env. Research 2022.
160. Wan et al. Synthesis of Cryolite (Na_3AlF_6) from Sec. Al. Dross Generated in the Al. Recycling Process. Materials 2020.
161. Ghazizade et al. Landfilling of prod. SPL in alu. Ind.: proposed method in dev. countries. 1st Int. C. on Final Sinks 2010.
162. Kristensen et al. Mindre deponering av farlig avfall. Bergfald Miljørådgivere 2019.

Base transition metals such as copper, manganese, titanium, zinc are also rather common in many alloys. For niche alloys,[163] elements such as lithium, neodymium, cerium, lanthanum, zirconium and even scandium, is used.

When post-consumer aluminium scrap is collected, it is only to a limited extent sorted into different alloys. Consequently, the niche alloying elements are to a large degree lost.[164] Partly into lower grade aluminium (casting) alloys, or in the salt slag from recycling.[165][166][167][168] The loss is for most of the metals equal[169] to the loss of aluminium of appr. 5% per cycle. Indeed, even if statistics say that some waste fraction will be fully recycled, in reality there is with today's technology a structural loss of several percent for each melting cycle.

Three Nordic countries have primary aluminium production, and the volumes of potential CRMs from SPL and dusts from these producers have been allocated to each country according to registered primary aluminium production in 2021. Dross from both primary and secondary production is treated in one particular plant,[170] and the numbers for that is allocated to the country of its residence. As the data for this plant is confidential, we have used average international compositional data combined with officially reported processing volumes.

The average gallium content of alumina, as used by the primary smelters in the Nordic region is appr. 70 mg/kg.[171] The primary production of aluminium was 1,7 million tons in 2022, hence a total inflow of appr 120 tons of gallium. This is much higher than the total European consumption, indicating that a proper extraction and recovery operation would be able to fully cover all EU/EEA needs. Indeed, as the information from the Nordic primary smelters have been lacking, we have been forced to use international reference data.[172][173][174][175]

Silicon industries

The Nordic countries have a large silicon industry, in particular with major upstream operations. This includes large quartz quarries, silicon metals producers such as Elkem and Wacker in Norway and Bakkisilicon in Iceland, ferrosilicon producers such as Elkem and Finnfjord together with silicon carbide producers such as Fiven and

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163. Teixeira et al. 2022. Optimization of Water Leaching of Chlorides from Aluminum Salt Slag. Minerals.
164. Arowosola et al. 2019. Est. div. and dissipative loss of critical metals in the alu. automotive sector. RC&R.
165. Jafari et al. 2014. Classification and Reactivity of Secondary Al. Production Waste. American Society of Civil Engineers.
166. Tsakiridi et al. 2016. Cyclones and fabric filters dusts from sec. alu.flue gases: a character. and leaching study. EST 2016.
167. Särkkä et al. 2018. Inv. of municipal solid waste (MSW) and ind. landfills as a pot. source of sec. raw materials. Detrius.
168. Wibner et al. 2021. Studies on the Formation and Processing of Al. Dross with Particular Focus on Special Metals. Metals.
169. Han et al. Effect of Flux on the Rec. Behavior of Valuable Metals during the Melting Process of Alu. Can Scrap. AMM 2021.
170. This plant is a client of Bergfald Environmental Consultants.
171. Aarhaug, TA. Aluminum Primary Production Off-Gas Composition and Emissions: An Overview. JMMMS (TMS) 2019.
172. Shimanskii, A. Alu. Smelting Carbon Dust as a Pot. Raw Material for Gallium and Germanium Extraction. JMMMS 2021.
173. Li, H. The Study of Carbon Recovery from Electrolysis Aluminum Carbon Dust by Froth Flotation. Metals, 2021.
174. Aarhaug, TA. Aluminum Primary Production Off-Gas Composition and Emissions: An Overview. JMMMS (TMS) 2019.
175. Adham, KG. Ac. and Chr. Eff. of Alu. Smelter Dust on Hemat., Metal Bioacc. and Oxidant-antioxidant st. in rat. ASD2020.

Washington Mills in Norway, and silicon nitride producers such as Vesta Si in Sweden. There are also several niche producers, such as ultrapure silica from The Quartz Corp and high purity silicon from Elkem.

In general, these value chains generate little slag compared to other metallurgical value chains,[176][177] and the slag comes in the smelter phase of the value chain. The volumes are included in the non-ferrous sector in the overall CRM statistics.

The dust from the smelters is a valuable material in itself that is sold.

EU has chosen to place silicon metal on the CRM list. That is probably mostly due to the downstream significance of the products, and not the availability of the element or the processing capacity upstream.

The Nordic metallurgical silicon and ferrosilicon smelters have rather small slag volumes, but the slag have a broad distribution of contaminant metals, partly received from the carbon sources.[178]

Recycling of postconsumer silicon products will, with a few notable exceptions, probably be rather costly and difficult compared to the ease of accessing quartz and other primary silicon sources. Solar panels are the main exception. While almost all solar panels have a long lifetime of use, there are some losses and waste. Extreme weather events or armed conflicts might destroy panels. When panels get old, in general more than 30 years, short circuits and other problems become more frequent.

176. Müller et al. Material Flow Analysis of FeSi Furnace at Elkem Bjølvefossen. NTNU 2020.
177. Hustad, H. Tapping of FeSi Furnaces. M.Thesis NTNU 2018.
178. Næss et al. Element Distribution in Silicon Refining: Thermodynamic Model and Industrial Measurements. JOM 2014

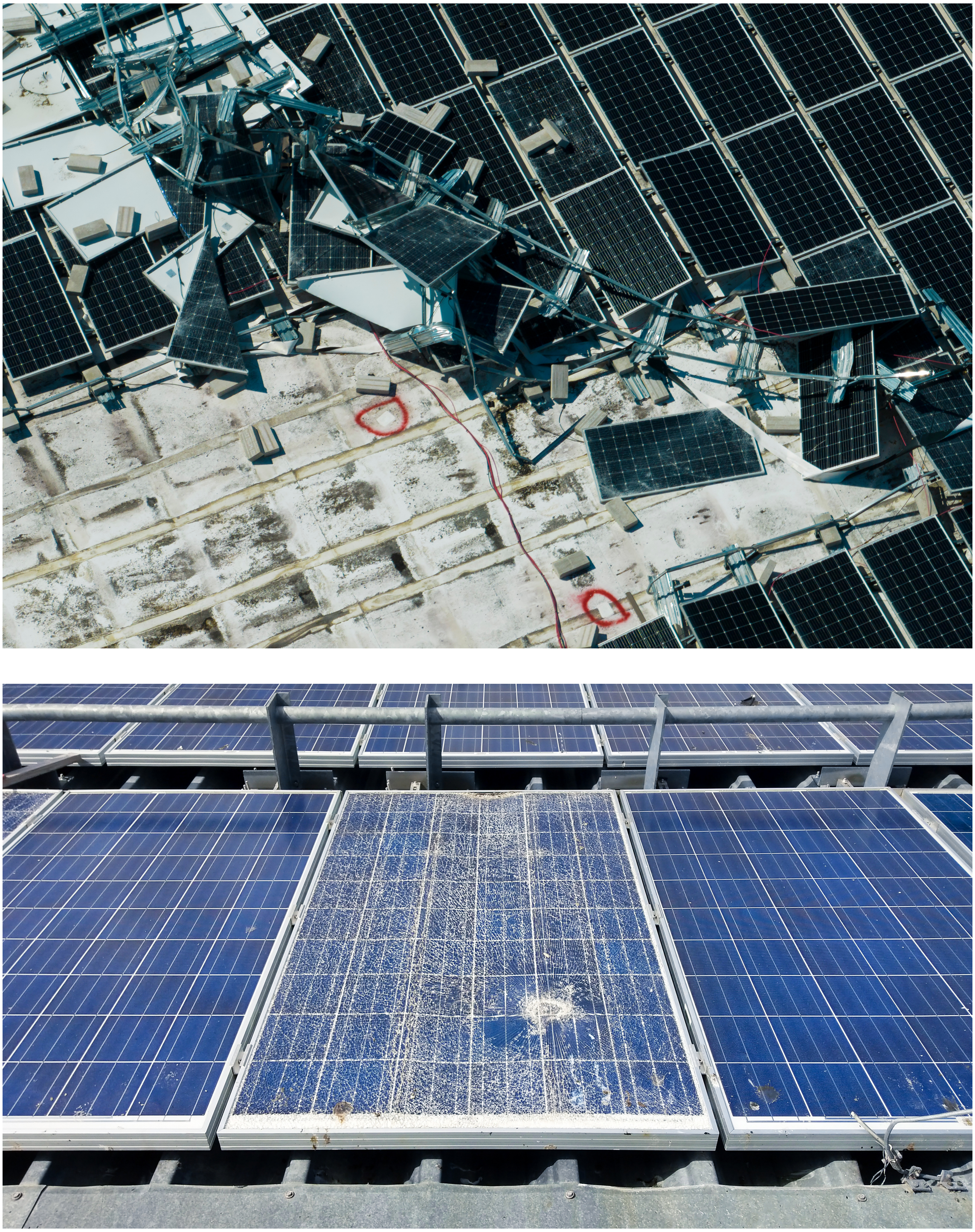

Figure A6 High age, extreme weather and war might destroy solar panels. Photo Adobe Stock.

Some of the panels installed in Europe and the Nordics are cadmium-based, but most are based on high purity silicon, with silver treads on the front, an aluminium frame and protected by a thin layer of silica-based glass in front. The volumes of scrapped panels are still small, but we should expect a sharp increase in the coming years, due to more of all the three factors destroying panels: age, weather and conflicts.

It is fair to say that on the one hand, it should be rather straightforward to efficiently separate the fractions in a solar panel. On the other hand, this sector is still not fully mobilized and developed.

Both metallurgical and hydrometallurgical methods have been developed to process the sorted silicon cell material.[179]

Other Industrial CRM-sources

Ferroalloys

The ferroalloy sector is large in the Nordics with four manganese plants in Norway: Ferroglobe Rana and Eramet Sauda, Kvinesdal and Porsgrunn. Combined, this sector produces appr. half a million ton of slag, dust and sludge. Silicomanganese slag dominates in volume and is currently marketed as "Silica Greenstone". This slag is chemically inert and contain very low levels of CRMs,[180] except for 2–5% manganese. The slag has historically been used as aggregate, but is increasingly used as clinker and concrete substitute. Based on the low level of CRMs, that might be the best application. However, the same smelters have some smaller volumes of 30–40,000 tons of filter dusts and scrubber sludges with some minor CRM levels.[181] These volumes have been included in the "other" category.

Norway also has significant ferrosilicon production with a plant in Finnfjord and the Elkem plants in Rana, Bremanger, Thamshavn and Bjølvefossen. Elkem also has a plant in Grundartangi, Iceland. These plants are producing relatively low volumes of slags and wastes, and the CRM levels are low. One exception to this might be the production of foundry alloys that takes place partly in Grundartangi and partly Bjølvefossen, as these alloys include magnesium and mischmetal from China. As the reported total volumes of slag is more or less one thousand tons, they have been included in this report.

In both Sweden and Finland, there is significant chromium steel production. This production is included in the steel section, while the Vargöen Alloys plant has been included in the Ferroalloys section.

179. Yi et al. Recovering valuable metals from recycled photovoltaic modules. J. of the Air & Waste Management Ass. 2014.
180. Miniggio et al. Environmental Aspects of Utilising Silicomanganese Slag as a Cement Substitute. B.Th Agder Uni. 2020.
181. Pedersen et al. Bærekraftig Gjenvinning av Metaller fra Manganslam via Syreleaching. Batchelor Thesis 2022.

Geothermal brines

Iceland has a large fleet of geothermal energy plants. These emit mineral rich water. In other countries, such geothermal effluents have proven rich in CRMs such as lithium. However, it seems that most of the brines currently used in Iceland are less CRM rich. Numbers from this sector are included in the statistics of this report, but only provide a minor contribution to the possible waste related CRM supply.

Pyrite ash

The burning of pyrite (iron sulfide) provides both processing heat and sulphuric acid. Sometimes, pyrite resources are influenced by copper-containing chalcopyrite or other transition metal sulphides.[182] As pyrite is still used, and even considered in new production – we have included the pyrite ash numbers in the "others" category.

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

WEEE

Waste Electric and Electronic Equipment (WEEE) is a term covering every manmade product through which electric current is supposed to pass and is strictly regulated by both the WEEE directive[183] as well as EPR schemes, RoHS and other relevant legislation. It includes obvious materials such as cables, computers and mobile phones, but also tiny items such as tiny sensors, memory sticks etc – items that are often overlooked and under-prioritized in collection schemes. Batteries are covered by its own regulation.[184] The CRM content and implicit increased recovery potential from WEEE sector is quantified in this report. As this sector is broad and wide, only a few component groups; PCBs, Motors, Cables, Screens/LEDs and batteries are evaluated. There are lots of other components and equipment parts in addition.

Printed Circuit Boards

Printed Circuit Boards (PCBs) carry quite many of the CRM-containing components in WEEE. Indeed, almost the whole periodic table is represented in a pile of mixed PCBs.

While there are other components with CRMs in WEEE, such as screens and motors, the PCBs dominate in complexity and also the overall volume for some of the elements. PCBs come in all sizes from huge server boards to tiny sensor

182. Oliveira et al. Chemical comp. and minerals in pyrite ash of an abandoned sulphuric acid production plant. ACP 2015.
183. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en
184. https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en

components. Composition is likewise highly diverse, with only metals such as gold and copper as common for all PCBs.

The collection of data on chemical composition of CRMs in PCBs over time is very extensive,[185] with more than 3,000 analyses of different PCBs. Recent numbers from Eurostat indicate a sharp increase in the sale of electronics all over Europe,[186] and a higher growth in sales than in waste collection. Another source from EU estimate that 400,000 tons of PCBs are placed on the market annually (2021).[187] A third source indicate that the annual global market for the composite resin used for the circuit boards are 1.76 million tons.[188] In total, 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 tons in EU. Indeed, our estimate would be that the Nordic countries have a market of 50,000 tons of PCB annually, of which 50% is returned to a WEEE scheme. 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 with welded or glued chassis are often sent directly to incineration without sorting.

Most importantly for CRM recovery though, is the smelters. PCBs are sent to major smelter hubs such as Boliden, Aurubis and Umicore with plants located in Sweden, Finland and Norway. These plants are originally built to process high grade copper ores, and have all 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, PGMs in addition to copper, as well as to some degree nickel, cobalt etc.

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[189] from the smelters, slags that are 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 is lost. Amongst the rest are 35 CRMs. As seen from the graphics below, the content of these non-recycled CRMs has increased over time, and most notably in the last few years.

185. Kristensen et al. Økt gjenvinning av kritiske råmaterialer. Bergfald Miljørådgivere for RENAS 2022.
186. www.ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment
187. www.cordis.europa.eu/project/id/761495
188. www.chemanalyst.com/industry-report/flame-retardant-resin-in-ee-composite-market-677
189. Andertun et al. Long-Term Leaching Effects on CaO-Modified Iron Silicate Slag. Minerals 2022.

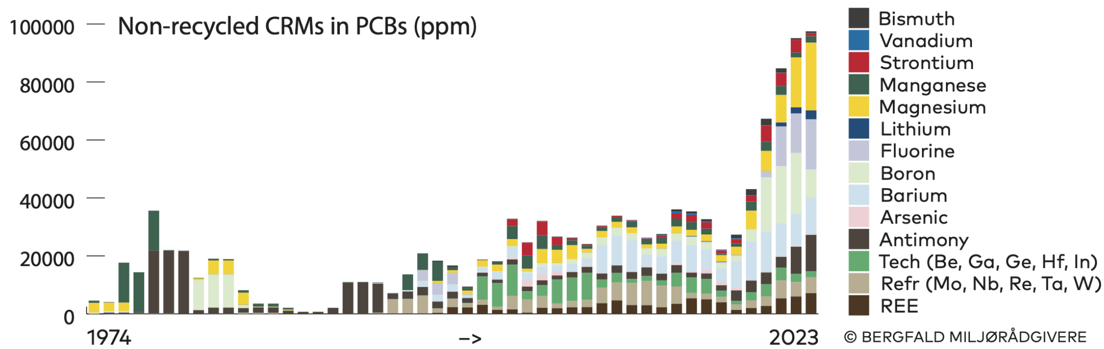

Figure A7 Increasing loss of CRMs from WEEE. While the EE-industry increasingly use advanced elements in electronics, the recycling industry keep focus only on a few elements, such as gold and copper. CRMs are lost in the recycling industry. Source and illustration: Bergfald Miljørådgivere.

Indeed, the overall situation is dire. Out of the 50,000 tons of PCBs placed on the Nordic market annually, almost all of the CRMs are lost; due to a multitude of challenges:

- Important sectors are exempt, such as automotive.
- Collection degree of small items is low, a lot is lost to MSWI.
- Industrial sorting is focused on copper/gold, with loss of minor items.
- Industrial recycling not able to recover 35 of the 45 CRMs found in PCBs.

Cables

Cables are a major consumer of large volume CRMs such as copper. In fact, cables are the main consumer of copper in all markets. Globally, the total market for cables and wires are estimated at 25 million tons (all segments, both Al and Cu cables), giving an annual consumption in the Nordic market off appr. 440,000 tons. A third of this tonnage is polymers. It is also expected that at least half of the tonnage is 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 rewiring, cables dug down in urban infrastructures etc. This copper, and its alloying and structural co-elements are neither lost, nor recovered. It remains available for urban mining at a later stage.

For our waste statistics, we have used the Norwegian statistics for large cables delivered for recycling in 2022, which was 18.721 tons. Norway represents 29,3% of the Nordic GDP, so estimated large cable supply would be 63.894 tons. In addition, there is some minor volumes from household cables, minor wiring etc, so we have set 65,000 tons as a conservative estimate.

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

Some of the cables that is reaching a waste processing plant is actually 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.

For the statistics, we have used an average of different types of cables and wires, such as this composition of standard copper cables,[190] electrical wires from EOL vehicles,[191] low voltage house electrical wires[192] and larger cables.[193]

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.[194]

Motors

Efficient electrical motors based on the strategic and critical raw material neodymium have been one of the most important game changers in modern industrial history. These efficient motors have made EVs more attractive than ICEs for the common man, as well as increased efficiency in electric components from the smallest sensor to the biggest windmill.

Statistics in this sector is however unreliable, partly due to rapid changes in magnet composition and motor design in EVs, increased reclaiming schemes from OEMs and a substantial aggregation of material in long term items such as power generators.

Based on access to industry insights,[195] a sjablon-based approach has been chosen for this report where non-REE PMs are ignored, as ferritic and AlNiCo-magnets have only limited CRM-importance and appr. 70% of the REE PM-consumption assumed to be in long term markets that will be unreachable for recycling operations for many decades. Further it is assumed that the composition of NIB and SmCo magnets are based on standards, company specific differences are ignored, ductility-improver only used for EVs and coating is 2/3 based on nickel and 1/3 based on tin.

At present, there is recycling capacity in Europe for neodymium from scrapped magnets which are unutilized. This is due to bottlenecks in collection and sorting of

190. Blinova et al. Importance of recycling the waste-cables containing copper and PVC. Slovak Tech Uni. 2021.
191. Lambert et al. Copper leaching from waste electric cables by biohydrometallurgy. Minerals Engineering 2015.
192. Basliu et al. Recovery of copper from waste cables used in electrical applications. Met. and Mat. Sc. 2015.
193. Celik et al. Recycling of waste electrical cables. Material Science & Engineering International Journal 2019.
194. 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.
195. Bergfald has been consultant on a regular basis to several REE companies since 2005.

magnets. A main topic for Nordic CRM strategies should therefore be how magnets can be efficiently collected for recycling.

LED/Screens

Diodes are very important components for several sectors. Almost all new light sources and illumination technology placed on the market is currently based on diodes, and almost all of these diodes are based on a gallium platform.

Similarly, screens are also increasingly based on diodes. Hence, we have for the statistics aggregated these different diode-containing component into one group.

So far, no significant recycling of WEEE-gallium exists. The current gallium recycling industry is only processing industrial scrap, although several teams are active at looking at different[196] mechanical,[197] pyrometallurgical[198] and hydrometallurgical[199] paths towards some recovery of gallium and other CRMs from post-consumer diodes[200] and lamps.[201]

Batteries

Batteries are one of the largest consumers of CRM metals today, and one of the sectors with highest growth. Still, the volumes of material available for recycling is low. Indeed, with the long operational life span of most CRM rich batteries, the battery sector can be expected to build up a large user pool of metals in the years to come. This growing sector will require large volumes of primary CRMs regardless of how well CRMs are recycled at the same time.

The statistical overview in this report shows that the dominant waste stream from batteries are still the old-timer lead-acid start batteries. These batteries are well proven and based on feedstock largely supplied in the form of waste or byproducts from other industries; lead from zinc refining and sulphuric acid from copper/nickel roasting. The lead-acid battery technology is mature, robust, cost effective but inefficient. The collection rate is very high, sometimes more than 100%, meaning that consumers are tidying and emptying old garages etc – which is a favourable situation. The collected batteries are sent to one central plant in southern Sweden. This Boliden owned plant specializes in battery recycling and recover battery materials very efficiently.[202] A minor slag and crust fraction is removed and disposed of in the Norwegian Boliden Odda mountain cavern.[203]

196. Rebello et al. Reciclagem de lampadas de led inserviveis : Panora atual e perspectivas futuras 2020.
197. Nagy et al. Recycling of gallium from end-of-life light emitting diodes. Arch. Metall. Mater. 2017
198. Chen et al. Recovery of Gallium and Indium from Waste LEDs. J.of the Korean Inst. of Res. Recycling 2020.
199. Wei et al. Opt. of extraction of valuable metals from waste LED via response surface method. Trans.N.M.Soc. China 2023
200. Mir et al. A Review on Recycling of EOL LED for Metal Recovery. The Minerals, Metals & Materials Society 2022.
201. Nikulski et al. The Potential and Limitations of Critical Raw Material Recycling: The Case of LED Lamps. Resources 2021.
202. Neistrøm, L. Characterisation of Used LABs for Feed Optimisation in Secondary Lead Production MSc Thesis 2018.
203. These numbers are included in the Jarosite-chapter.

Lead-acid-batteries show fluctuations in material composition over time, for example regarding the content of antimony and bismuth as lead alloy materials. While most of the start batteries are used for mobile applications such as cars, there are also niche markets for stationary applications such as power banks for solar cells at cabins etc.

As antimony is classified as a CRM, and the lead in start batteries normally is alloyed with antimony, this could be a possible future source. However, unless the societal needs for antimony changes from today – it seems unnecessary to take any significant initiatives towards this material stream. The recycling rate is high and efficient, and the materials are available if needed.

In the statistics of this report, a list of references is used[204] as average for these batteries and these numbers are purely recorded from Sweden, due to the location of the recycling plant.

The alkaline batteries are well known household applications such as flashlights, smoke detectors or toys. Historically, these batteries had high levels of mercury and represented significant environmental risks. The last decades they have however been based on different compositions of zinc and manganese, of which only manganese is considered CRM. As these batteries are small, the collection rate is not that great. According to Eurostat, the category Portable Batteries have a Nordic collection rate varying from 47% in Sweden to 77% in Iceland.

Portable batteries are sorted manually at the EPR plants in the Nordic countries. The alkaline batteries[205] are sent to recycling plants[206] outside of the Nordics for recovery of zinc, which is not a CRM. In these recycling plants, the batteries are mixed with other zinc waste and fossil coke and cooked. Most of the zinc, approximately 80–90%, is recovered, while the battery grade manganese is mixed into a slag unsuitable for further processing. In all statistics, these tonnages of collected and sorted wastes with appr. 25% CRM[207] content is registered as recycled, while in reality – the CRM content is all lost. This issue is also mentioned in the EAF dust chapter as a problem to be looked into. It is an obvious opportunity to implement recycling technologies for these batteries with a better performance than today. Indeed, one recommendation would be to consider the ban on processing of such sorted CRM-containing wastes in ways that immobilize the CRM.

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204. Ogheneortega, Oji John. Harnessing Nigeria's Abundant Lead Ore Deposits for the Dev. of LAB Materials. Nat. & Sc. 2012.
205. Falco et al. Study of a pilot plant for the recovery of metals from spent alkaline and zinc-carbon batteries with biological sulphuric acid and polythionate production. Lat. Am. appl. Res 2014.
206. Ebin, Burçak. Investigation of zinc rec. by hydrogen red. ass. pyrolysis of alkaline and zinc-carbon battery waste. WM 2017.
207. Romo et al. From spent alkaline batt. to $Zn_xMn_{3-x}O_4$ by a hydromet. route: synth. and characterization. RSC Advances 2018.

Portable batteries based on Nickel-Cadmium[208][209] (NiCd) or Nickel-metal-hydride[210][211] (NiMH) are typically used for power tools. Also in this sector, LIB batteries have increasingly taken over, but the legacy volumes keep coming in and will keep doing so for several years. Some data for these batteries are available, mainly due to the need for the environmental authorities to keep monitoring the cadmium flow.

The NiMH are the only batteries with rare earth content. It is not uncommon to talk about rare earth as an important input in batteries for the Green Shift, but that is an outdated perspective based on NiMH. The first fleet of any major size of modern electric vehicles was the Toyota Prius, a HEV equipped originally with a NiMH-battery. The NiMH design at the time was based on mischmetal, a commonly used tradename for a mixed rare earth metal. Mischmetal at that time was just crudely processed LREE that was reduced without prior separation. The main use for mischmetal at the time was for lighter flints and in cast iron inoculants. When the Prius became popular, that stressed the mischmetal market, and provided shortcomings in the supply chain, creating a myth about difficulties in providing needed rare earths in EV batteries.

Three conditions have changed since the early days of Toyota Prius; all EVs are now on different lithium platforms without the need of any REEs. LREE separation technology has drastically improved in performance and costs, separating the current mischmetal components cerium and lanthanum from the remaining REEs. Most importantly, the market for neodymium has drastically changed the REE industry with the result of lanthanum and cerium currently being classified as low cost/worthless byproducts. Nobody can afford letting neodymium be in mischmetal anymore, so mischmetal today is a lanthanum-cerium alloy produced from separated LREEs.

Anyway, NiMH legacy batteries are coming in, but only the nickel content should be regarded as both valuable and critical today, lanthanum and cerium are not.

Lithium based batteries was developed by a team of chemists under the brilliant leadership of John B Goodenough – a later recipient of the Nobel Prize in Chemistry.[212] While the creativity of the chemistry team was excellent, the lab facilities was limited. By coincidence, a small bottle of cobalt sulphate was available, and that coincidence was the start of many later difficult issues.[213]

A lithium battery moves the electricity with the charge of the very small lithium ion. Lithium is the third element of the periodic table, only hydrogen and helium are smaller. Indeed, there are no elements able to carry an electric charge better than lithium. But the lithium charge carrier is a very small part of a lithium battery, only

208. Huang, K. A Novel Process for Recovering Valuable Metals from Waste Nickel–Cadmium Batteries. ES&T 2009
209. Blumbergs et al. Cadmium Recovery from Spent Ni-Cd Batteries: A Brief Review. Metals 2021.
210. Lin, Sheng-Lun. Char. of spent NiMH batteries and a preliminary econ. evaluation of the rec. processes. JA&WMA 2015.
211. Shin et al. Recovery of el. Powder from spent NiMH batteries. Arch.of Met. and Materials 2015
212. https://www.nobelprize.org/prizes/chemistry/2019/summary/
213. Goodenough, John B. How we made the Li-ion rechargeable battery. Nature Electronics 2018.

2–3% or 8–12 kgs of an EV battery of 4–500 kgs is lithium. The bulk of the batteries are graphite in the anode and the transition metals nickel, manganese and cobalt etc in the cathode, and surrounded by the aluminium casing holding all in.

Getting back to the small battle of cobalt sulphate in the lab of chemist Goodenough; cobalt is not really any better than nickel and several other of the transition metals. But from a supply perspective, it is very different. When the first lithium battery was introduced to the market on a LCO platform, the global cobalt industry was only 33,000 tons, and the new batteries immediately spurred a global frenzy, including shortcutting supply lines with unacceptable mining operations in Congo.

Had the first lithium batteries been started with nickel instead, which is as good as cobalt, the global supply line would have started at more than 1 million ton, not creating any mining stir at all.

As the current global consumption of cobalt into the battery industry 30 years later is appr. 120,000 tons, it is obvious that a small bottle of nickel sulphate instead of cobalt sulphate would have started this industry on a much more sustainable footing. Indeed, today nickel is the main battery metal, and cobalt is used in smaller volumes and increasingly in smaller niche applications. It is not entirely obvious that there are any new batteries produced and sold in the Western world based on cobalt at all in 2030.

We were not successful in finding reliable data on the different battery chemistry of high voltage batteries that are finally disposed in the Nordic. We have tried several written and oral attempts towards the responsible EPR scheme in Norway, without reply. Hence, we have based the battery figures on a UK report, where extracted black mass has been analysed and reversed engineered combined with a look at sales statistics 5–10 years back in time. The adapted estimate for the Nordics is henceforth tainted with significant uncertainties. It should also be noted again that battery chemistry is developing fast and slightly unpredictably, adding to even more uncertainties when considering future volumes.[214][215] Still, as we need to have figures, we have used the following estimates on distribution on different LIB chemistries (for discarded, not sold, batteries): LMO 10%, LFP 10%, LCO 10%, NMC111 10%, NMC532 5%, NMC622 5%, NMC811 5%, NCA 10% and others/unknown 35%. These figures are obviously not entirely accurate, but as we do not know neither the tonnages of collected LIB batteries or the composition of the second life batteries, it is best estimate as of now.

214. Turek, A. The Necessity of Rec. of Waste LIB Used in EVs as Objects Posing a Threat to Human Health and the Env. 2018
215. Gaines, L. Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling. Argonne National Lab 2011.

Figure A8 Companies like Akkuser (Fi) and Hydrovolt (N) are providing excellent LIB recycling services.[216] However, as LIB batteries have a long lifespan, the tonnage coming from these recycling plants will be limited for quite many years.
Photo top Akkuser.
Photo bottom Hydrovolt.

Research published in 2023 has shown that spent EV batteries have less lithium in the batteries than listed in the specifications,[217] indicating that it could be a loss of lithium/migration out of the batteries during the lifetime.

216. Dykes, Blake. The recycling of Lithium batteries. MSc Thesis University of Queensland 2018
217. Waidha, A. Recycling of All-Solid-State Li-ion Batteries: A Case Study of the Separation of Individual Components Within a System Composed of LTO, LLZTO and NMC. ChemSusChem 2023

Regarding the tonnage, we have estimated that the current situation is a steep aggregation of batteries, with sales of new EVs far outperforming the return of damaged and EoL LIB batteries.

Hence, we have sjablon-based our estimate at a total LIB-collection of 20% of current sales of EV-batteries, that the current sale is 200,000 units of 400 kgs each; resulting in 16,000 tons of LIB-batteries. We expect tonnage to grow significantly in the coming years, and the composition to change as much.

It should be mentioned by many lithium batteries, particularly the portables, contain relevant levels of thallium.[218] This is a rare element of very few uses, and with very hard restrictions in the EU area due to toxicity. However, it is regarded as CRM in some other nations and used in electronics and batteries. As the EU market is flooded by lithium batteries with dubious composition , mitigations must be made at recycling plants to avoid environmental or health problems from thallium.

Waste tires

Waste tires is a huge and rather homogenous waste fraction, generated in consistently large volumes.

The differences in composition between summer and winter tires, personal vehicles and buses, between different suppliers etc is minor compared to heterogeneity in most other waste fractions. While tires consist mainly of natural and synthetic rubber, it also has a high content of inorganic components. Some of this is the steel alloy fibres, but also the rubber itself has a high inorganic (metal) content. Some of these metals are intentionally used as additives to optimize tire properties, some of the metals are contaminants from processing, such as catalysts, some are natural contaminants from the growing of Hevea[219] and some metals are even absorbed by carbon black in the rubber from the environment.[220]

The synthetic SBR part of the tires is mostly produced with neodymium catalysts, efficiently dissipating about 1000 tons of neodymium annually on a global basis. As such, neodymium sufficient to build 1 million electric cars is lost into car tires - globally. If this is possible recover from the rubber has yet to be decided.

Although used tires in the Nordic countries is reported in national waste statistics as fully recycled, CRMs in the tires are not. Car tires shredded and used as filtering medium in landfill is classified as recycling, as does export to Turkey for use in clinker plants, so the potential for better recycling efficiency should be obvious, not only regarding CRMs. Indeed, projects are now maturing trying to implement cryo- or pyro-technologies for real material recycling of parts of the composition, for example carbon black (REF). One of the benefits with these technologies is that it

218. Kang et al. Potential Env. and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste. ES&T 2013.
219. Thepcalerm, C. Study of the mesostructured by AF4-MALS and of the mineral element comp. by ICP-MS. PhD Th. 2014.
220. Shahraki et al. High eff. Removal of heavy metals using tire-direved activated carbon vs commercial activated carbon: insights into the adsorption mech. Chemosphere 2021.

also liberates steel fibres and some of the other inorganic content. One project of particular interest could be the new plant of Svensk Dekkåtervinning, and the possible downstream processing by Rubber Innovation. This site might be further developed to also extract and recover some of the critical metals content. It could be that pyrolysis will open up the path towards recycling of lot of inorganic material of high value.[221]

For the statistics in this report the average content of several reports has been averaged, considering the difficulties of ICP analysis of a material such as rubber. Reports from Germany,[222] Portugal,[223] Argentine,[224] South Korea,[225] UK,[226] Sweden,[227] Ukraine,[228] Hellas[229] have been used as basis.

National annual volumes of scrapped tires are estimated at 70 kt for Norway, 90 kt for Sweden, 50 kt for Finland, 40 kg for Denmark and 5 kt for Iceland, based on conversations with tire return schemes and recycling industry representatives in the Nordics.

Suggestions for improved legislation:

- Ban the use of waste tires as infill/drainage layers of landfills.
- Ban the export of waste tires out of EU/EEA, including export to Turkey, Morocco etc.
- Incentivize the development of non-Neodymium SBR-production.

The shredder plants

The largest and most visual component of the Nordic recycling infrastructure is the shredder plants. Large, metal-containing waste such as scrapped automobiles, production machines, cables, pole etc has for centuries been collected, sorted and recycled due to inherent metal values. Increasingly, as the society has taken 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.

Today, cars and other large equipment is received, oils and hazardous materials such as lead batteries are removed before the remaining components are beaten and shredded into small pieces in large mills. The main set up for these shredding mills include multistep separation towards iron with magnets, aluminium with Eddy

221. Naveed et al. Gasification Characteristics of Auto Shredder Residue. J.Chem.Soc.Pak. 2011
222. www.dgengineering.de/download/open/Presentation-Scrap-Tires-2013.pdf
223. Nogueira et al. Char from Spent Tire Rubber: A Potential Adsorbent of Remazol Yellow Dye. J.ofCarbon Research 2019.
224. Trezza et al. Scrap Tire Ashes in Portland Cement Production. Materials Research, Vol. 12, No. 4, 489-494, 2009
225. Jeong et al. Toxic metal conc. and Cu–Zn–Pb isotopic comp. in tires. Journal of Analytical Science and Technology (2022.
226. O'Loughlin et al. Analysis of Tyre Tread for Metal Tracers with Applications in Environmental Monitoring. Env. Int. 2023.
227. Lönnermark et al. Emissions from Tyre Fires. SP Fire Technology 2005.
228. Khrunyk et al. EIA of alternative fuels co-processing in rotary cement kilns. Inżynieria i Ochrona Środowiska 2014.
229. www.eng.auth.gr/mech0/lat/PM10/Tyre%20wear-tyre%20and%20particle%20composition.htm

current and copper/brass with sieving, hand sorting or flotation. Some of these plants have developed over time into even more detailed separation systems, being able to distinguish between different alloys to a certain degree.

This industry is the main recycling infrastructure in the Nordic countries, it is represented with several plants in Norway,[230] Sweden,[231][232][233] Denmark[234][235][236] and Finland.[237] 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 unshredded 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 these plants are receiving are containing increasing levels of CRMs, this industry today represents one of the potentially largest losses of Critical Raw Materials, and at the same time a sector where similar potential for CRM-recovery with limited efforts of costs.

The metals

So far shredder plants are mainly built to recover the three main metals; iron, aluminium and copper. Legislation, permits, technological recycling concepts are all geared towards this. However, the metal coming out of these shredder plants are far from homogenous often containing 5–10% of other metals than the main metal. A thorough report from Germany in 2020 showed that the iron fraction from shredding of used cars actually only contained 92% iron. The rest was other metals, like aluminium, zinc and several CRMs.[238] When this material is sent to the EAFs, it is regarded as 100% recycling. When remelted, some of the iron goes into the recycling slag, as well as some of the alloying elements. Indeed, when considering the steel coming out of the EAF plants compared to the feedstock going in – the real recycling rate is closer to 85–90%. The same issue is present for aluminium and copper – the main metal will represent 90–95% of the fraction, other metals will make up the rest and both alloying elements, contaminants and base metals are lost in the processes. When metal from shredder plants arrive at the recycling plants; the EAFs, the secondary aluminium smelters etc, these contaminants are very important to monitor and compensate for, and increased recycling of minor CRM components should be possible through optimization of the recycling processes.

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230. Hovde, L.R. Analyser av lettfraksjon fra fragmenteringsverk. Hjellnes Consult 2007.
231. Stanicic a et al. Fate of lead, copper, zinc and antimony during chemical looping gasification of ASR. Fuel 2021.
232. Faust et al. Interactions between ASR and Olivine BedMaterial during Indirect FB Gasification. Energy&Fuels 2021
233. Jagodzinska et al. Can torrefaction be a suitable method of enhancing shredder fines recycling? W. Management 2021.
234. Nedenskov et al. Shredder Waste and mixed waste, DHI Miljø 2011.
235. Hjelmar et al. Treatment methods for waste to be landfilled. TemaNord 2009:583
236. Boldrin et al. Life cycle assessment of shredder residue management. Miljøstyrelsen 2015.
237. Nieminen et al. Gasification of shredder residue. VTT 2006.
238. Sander et al. Evaluierung und Fortschreibung der Methodik zur Ermittlung der Altfahrzeugverwertungsquoten durch Schredderversuche unter der EG-Altfahrzeugrichtlinie 2000/53/EG. Umweltbundesamt 2020.

Figure A9 A scrap bin in a Norwegian iron foundry, promoted by the Auto Recycling scheme Autoretur.[239] In the background, another heap can be seen – this is pure virgin pig iron, necessary to dilute and compensate the many contaminants in the car scrap. The pig iron in the picture is produced from African beach sand. Photo Autoretur.

Iron

Some of the metals following the iron, such as chromium and nickel will mainly stay in the steel and provide some minor benefits. However, for many of the other metals, the metals can make problems. Manganese will mostly migrate to the slag and be lost. Zinc will evaporate from the furnace, then cool down and precipitate in the EAF dust, where it might later be recovered. Copper, on the other hand, mainly stays in the iron, and is an increasing problem for the steel industry.[240]

239.https://autoretur.no/slik-blir-deler-av-bilen-til-kumlokk/
240.Daehn et al. How Will Copper Contamination Constrain Future Global SteelRecycling? Environ. Sci. Technol.2017

Tabelle 204: Rechnerische Zusammenstellung der in der Fe-Fraktion enthaltenen Elemente

Element	Schredder-anlage 1 Kiste 1 [mg]	Schredder-anlage 1 Kiste 2 [mg]	Schredder-anlage 1 Kiste [mg]	Schredder-anlage 1 (Gesamt-masse) [mg]	Schredder-anlage 1 [mg Stahl-produkt]	Schredder-anlage 1 [Gew%]	Schredder-anlage 2 [mg]	Schredder-anlage 2 Kiste 2 [mg]	Schredder-anlage 2 Kiste [mg]	Schredder-anlage 2 (Gesamt-masse [mg]	Schredder-anlage 2 [mg Stahl-produkt]	Schredder-anlage 2 [Gew%]
Ag (ICP-OES)					n. n.						n. n.	
Al	94.050	190.393	1.096.410	1.380.853	11.973	1,20	189.120		1.641.651	1.830.771	16.532	1,65
Bi					n. n.						n. n.	
Co			12.045	12.045	104	0,01					n. n.	
Cr	76.751	33.537	38.715	149.003	1.292	0,13	79.940	8710		88.650	801	0,08
Cu	3.7364	153.865	1.955	193.184	1.675	0,17	82.580	39641	804.942	927.163	8.372	0,84
Fe	4.7644.988	38.336.431	23.257.525	109.238.944	947.186	94,7	25.695.520	39054488	37.334.804	102.084.812	921.842	92,18
Hg					n. n.						n. n.	
Mn	165.032	71.058	65.810	301.900	2.618	0,26	89.070	136530	238.508	480.930	4.343	0,43
Mo	13.396			13.396	116	0,01					n. n.	
Nb					n. n.						n. n.	
Ni	18.374	6.175	5.745	30.294	263	0,03	103.660			103.660	936	0,09
Pb	6.961	13.200	227.755	247.916	2.150	0,22					n. n.	
Pd (ICP-OES)					n. n.						n. n.	
Sb					n. n.						n. n.	
Se					n. n.						n. n.	
Sn					n. n.						n. n.	
Ti			68.795	68.795	597	0,06	48.950			48.950	442	0,04
V			2.220	2.220	19	0,002					n. n.	
W					n. n.						n. n.	
Zn	29.170	136.932	517.835	683.938	5.930	0,59	1.230.430	837376	1.003.182	3.070.987	27.732	2,77
Zr					n. n.						n. n.	
Au (ICP-OES)					n. n.						n. n.	

Figure A10 Example of actual content of iron fraction from an automotive shredder. (Facsimile from Sander 2020).

As steel scrap currently contain 0,2–0,5% copper, and increasingly, steel is arguably one the largest sinks or sources of loss of this CRM. The losses of copper into steel alone represents volumes comparable to the full production from 10–20 medium sized copper mines. Indeed, improved sorting at shredder 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 has entered the recycled iron melt, it cannot be extracted without huge energy costs and losses of material. Indeed, the industry handles this today with blending of different scraps and dilution with pig iron as well as systematic downcycling. Scrapped car steel is used for rebar and manhole covers – only to a limited extent is it used in new cars.

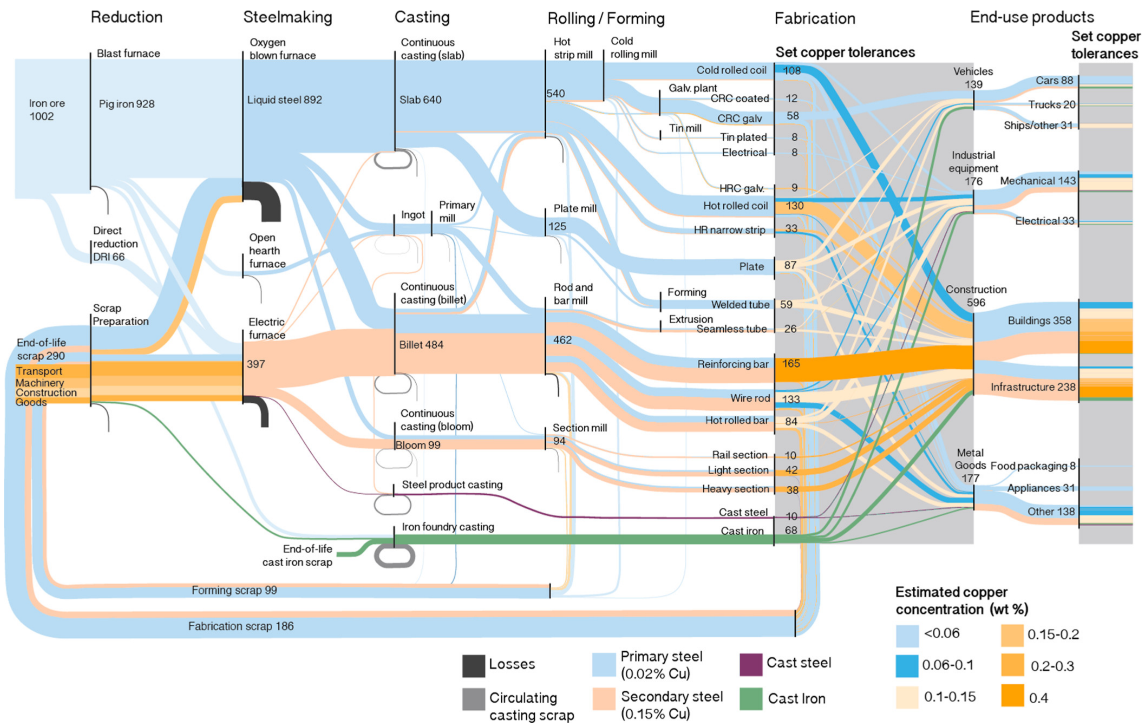

Figure A11 Systematic downcycling of iron from high end to low end applications to avoid copper contamination. (Daehn et al)
Illustration Environ. Sci. Technol. 2017, 51, 11, 6599-6606.

As recycling degrees of iron increases, this will become an intolerable problem mandating new and strict upstream separation requirements.

Aluminium

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"* [241]

The problem has been clear for some time. High quality aluminium from extruded, rolled or wrought components have been mixed together and used as feedstock for casting components, efficiently making casting alloys the trash bin and end station for aluminium. Indeed, already ten years ago, the Norwegian Aluminium Industry expressed concerns that the casting alloys sector had been filled up with scrap from automotive recycling.[242]

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

241. www.european-aluminum.eu/wp-content/uploads/2022/08/irt-m2p-executive-sum-20210412-final-2.pdf
242. Modaresi et al. Component- and Alloy-Specific Modeling for Evaluating Alu. Recycling Strategies for Vehicles. JOM 2014.

Figure A12 Tomra and more are working on aluminium alloy sorting. Improvements are needed.
Photo Tomra.

In secondary aluminium plants it is common to treat the incoming scrap with different chemicals to get as much of the contaminants out before casting. This is detailed more in chapter regarding the aluminium industry, and the high content of CRMs in the drosses, salts and dusts from that industry. However, as most of the contaminant metals stays in the aluminium, there is at present a systematic downcycling of aluminium which is unsustainable.

The fluffy fraction – and the 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 is as the word says the finer particles and dusts 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 categorized as "shredder residues", a material that has no market value but must be disposed of as waste. Importantly, 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 very small sensors etc – the many tiny bits and pieces ends up as a large total loss.

Fluffy electronics

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.[243]

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 (computer, laptops, entertainment units, mobile phones, TVs, music systems etc). As an example, the reported volumes of shredder residues and the average levels of CRMs reported in them indicate an annual loss of 112 tons of neodymium and 11 tons of dysprosium. That is a volume from which 200,000 fully electric cars could have been produced – if the CRMs had been fully recovered.

Post-shredding separation of these many small items seems difficult and costly, though not entirely impossible. It may in fact be a more resource efficient and cost-efficient path to implement routines and regulations for pre-shredding dismantling of all car electronics, including sensors, and specific recycling mandates of such components equal to that of the consumer electronics.[244] Modern automobiles, whether it is ICEs or EVs contain a lot of small motors; for example window wipers, window hoists, electronic locks, seat adjustments, air fans etc. 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, buses etc) are exempt from the WEEE regulations that almost all other sectors are mandated by. Hence, this feedstock is currently lost into the shredder residues. Indeed, one of the lowest hanging fruits for increased CRM recovery before 2030 would be for the automotive electronics to be included in the WEEE mandates or have equal recycling requirements as all other electronics in the 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 in the years ahead.

Mass calculations

Cars and other equipment sold in different countries might have some minor differences in composition of critical materials that are ignored in this report. In establishing estimates of CRM content in these waste fractions, there are other parameters of much more importance. That would include sampling methodology,

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243. Restrepo et al. Stocks, Flows, and Distr. of Critical Metals in Embedded Electronics in Passenger Vehicles. ES&T 2017.
244. Restrepo et al. Effects of car electronics penetration, integration and downsizing on their recycling potentials. RC&R 2020.

particle size, and time. For example, cars sold in Germany and Finland in 2010 had higher similarity in CRM-content than cars sold in either of the countries in 2010 and 2020. Indeed, time is more important than markets.

As to the total tonnage of shredder residue, insufficient updated data have been available. We have therefore used reported tonnages for the different countries from 1999 and multiplied with GDP development. That ends up with a shredder residue total of 638,000 tons. We have in parallel multiplied the numbers of scrapped cars in 2020[245] with an assumed average weight of 1500 kgs per ELV, 20% ASR per ELV and a 50% dominance of ELV in the SR. Conclusively, we have conservatively used 638,000 as basis for our calculations.

Finnish shredder residues are one of the few analysed for PGMs. Characterisation of shredder fluff and its content of minor WEEE-related CRMs.[246] It is found that the shredder fines contain high concentrations of CRMA metals,[247] probably much higher than many of the other fractions.[248]

Swedish work on use (and hence source) of CRMs in cars have been useful for calculating the overall numbers.[249] Sweden has already done substantial and important work[250] to map the potential of CRM recovery from several sources.[251] Some of them have moved closer to implementation of industrial solutions.

To compliment lack of Nordic data, we have also included average numbers from ASR in UK,[252] Italy[253] and Ireland.[254] We have also included global references on shredder residue composition.[255] Please note that quite a lot of Norwegian scrapped cars are periodically sent to UK and Ireland for shredding.

Shredder residues will typically have two disposals in the Nordics; the fluff consisting of mainly plastic and rubber with small pieces of metal in it 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 highest recycling and supply interest.

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

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245. www.ec.europa.eu/eurostat/statistics-explained/images/0/03/End-of-life_vehicles%2C_2008%E2%80%932020_%28number%29_2023-07.png
246. Jalkanen et al. On the direct recycling of automotive shredder res. and electronic scrap in met. Ind. A. Met. Slovaca 2006.
247. Widmer et al. Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output. Supporting
248. Naidoo, A. An inv. of prop. of shredder fines and anal. of ash to find new ways of dealing with this waste. M.Thesis 2020.
249. Cullbrand et al. The Use of Potentially Critical Materials in Passenger Cars. Chalmers 2012.
250. Haindl, S. Process analysis and concepts for thermal treatment of waste. MTh. 2016. Chalmers Uni.
251. SGU. Hållbar utvinning och återvinning av metaller och mineral från sekundära resurser. Regeringsuppdrag 2023.
252. Khodier et al. Challenges around automotive shredder residue production and disposal.
253. Ferella et al. Extraction of metals from ASR: Preliminary results of diff. leaching systems. Chinese J.of Chem. Eng. 2015
254. ELVES. Analysis of ASR from the Composition, Recycling and Recovery Trial for ELV in the R. of Ireland. 2016.
255. Sakai et al. An international comparative study of end-of-life vehicle (ELV) recycling systems. JMCWM 2014.

Figure A13 Landfilling of shredder fines results in fires instead of recycling.[256] Photo Varden.

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,[257] and is not without its issues, for example 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.

The large question both for CRM recycling and for the quality of the iron, aluminium and copper coming out of the shredders are whether smashing waste together before sorting is a good idea. In order to improve qualities of both the main fraction of iron and aluminium – and provide a better possibility for CRM recycling, a development of this industry in direction of pre-shredder dismantling and sorting is the fundament.

Recommendations for future work:

- Consider structural changes to the shredder industry with mandates of increased pre-shredder sorting.
- Include all rolling equipment in all WEEE mandates. Mandatory electronics removal.

256. www.tv2.no/nyheter/innenriks/kraftig-brann-i-avfallsanlegg-i-skien-er-under-kontroll/9252471/
257. Johansson et al. Separate comb. of selected waste streams to increase resource recovery from ashes. Re:source 2017.

- Ban on landfilling of shredder residues.
- Ban on incineration of shredder residues with >1% CRM metals.

Ashes

The Nordic countries generate around 6 million tons of ashes from incineration of waste and biomass. Some of the ashes are utilized, as concrete replacement or fertilizer, while most of the tonnage is landfilled as either inert or hazardous waste. The levels of total CRMs in these ashes are averaging around 1% - 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.

Ashes from waste incineration and biomass contain most of the periodic table.[258] While the average grade of different CRMs is rather consistent over time, there are huge differences between different ashes based on what materials are incinerated. Some ashes contain levels of CRMs similar and even higher than commonly used primary ores and others are very low.

The feedstocks for the biomass plants are also different.[259] While all countries use different type of wood/forest related feedstock, Finland have in addition significant volumes of peat,[260] while Denmark have significant volumes of straw. Some of the countries incinerate sludge from wastewater treatment, others use it is direct fertilizer. 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.

Despite differences in origin and composition, the ashes are created every day, and will be indefinitely. If anything, it is more likely that the sector will increase rather than decrease in the years ahead.

As an illustration, the Nordic ashes contain a third of the regions need for REEs and all its need for the recently export-restricted CRMs gallium and germanium. The content of praseodymium/neodymium in the Nordic ashes would, if all is recovered be sufficient to build 200,000 electric cars – or approximately the current sale of EVs in the Nordic countries.

MSWI ashes has historically been regarded as problematic and sometimes hazardous which has created a need for safe disposal.[261] Hundreds of projects globally have used bottom ash as filler material in building projects,[262] and fly ash has been used as concrete addition, but only recently has the ash been seen as a possible feedstock of important metals.[263]

258. Kalembkiewicz et al. The Physicochemical Prop. and Comp. of Biomass Ash and Ev. Dir. of its Appl. Pol. J. Env. Stud. 2018
259. Dijen, F. Bioefficiency - Influence of pre-treatment, blending and additives on ash composition (D6.2). 2019.
260. Perämäki et al. Occ. and rec. pot. of REE in Finnish peat and biomass combustion fly ash. J. of Geochemical Expl. 2019
261. Holmstrøm, P. Aske som ressurs. Avfall Norge, 2012.
262. Maresca et al. Life Cycle Assessment of future management options for Danish MSWI fly ash. MST report 2019.
263. Skåra, A.R. Gjenvinning av verdifulle grunnstoffer fra saltutvasket flyveaske. M.Th, University of Oslo 2022.

Over time and due to adequate environmental legislation, the content of hazardous metals such as lead, mercury and cadmium have been declining. As electronic products get smaller and more advanced, the content of valuable metals such as copper (and gold) are slightly increasing in the products – and the increasing numbers of small items that end up in mixed waste fractions that are incinerated ends up in the ashes. Insufficient data makes it difficult to conclude, but our expectation is that the levels of minor metals, particularly the WEEE-related CRMs, are increasing both in concentration and tonnage.

While WEEE schemes all over the world, and in particular 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 was originally 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 would be parcel ID trackers, toys, gimmicks, airpods, memory sticks, credit cards, ID cards, pointers etc. These generally end up in the MSW and later on the metals are found in the ash.

Toys are recently highlighted as a tsunami of WEEE waste.[264] In just a few years it has become common, and inexpensive, to put electronics into any and all toys sold. This year, it is estimated that 7,3 billion items of 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 would expect close to 100% loss of the contained metals from these items to end up in incineration ashes.

Weight and volumes

When both waste and biomass is incinerated, many chemical reactions are active in sequence. Volatile metals such as zinc, thallium, mercury and cadmium tend to evaporate and precipitate either in the fly ash, while refractory metals such as molybdenum and rhenium stays in the bottom ash. This is similar for both waste-based and biomass-based incineration. Difference in design of the incineration process will to some degree influence speciation.

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. As an example, aluminium components in MSWI plants absorb some CRM metals during the incineration – ending up with a different alloy composition than what was fed in.

264. 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/

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

A huge source of biomass ash comes from the forest industries. Indeed, almost all pulp, paper and wood processing plants have CHP boilers making their own steam from bark, sludges etc. Some of these boilers have been adapted also to use other feedstocks. For example, the Norwegian plant Norske Skog in Skogn operates a combined boiler for bark and sludge from recycled paper. The 25,000 tons of ash from this boiler has a high content of calcium, aluminium and silica from the paper fillers, but also high levels of some other metals. We have not differentiated these plants – all are included as bio ash in the statistics.[265]

Iceland does not operate regular MSW Incineration plants and is instead exporting its waste. As far as we understand it, most goes to Sweden, but that will probably differ from year to year. As far as we know, there are no significant biomass boilers in Iceland, so bio ash production is limited to households and microunits. These volumes will be unpractical to collect, so it is ignored in this work.

Most of data for bio ash is combined fly ash, bottom ash, scales etc. As volumes of bio ashes increases, and technology for extraction of CRM matures – more detailed reporting should be initiated. There are large and systematic compositional differences between fly ash and bottom ash. There is also a significant difference in composition between urban and rural dominated ashes.[266]

It has been conducted work in Denmark for mapping of REE and other CRMs in ashes from such different sources as MSWI in Greenland[267][268] and biomass in Denmark.[269] Several Nordic initiatives are active in trying to extract valuable materials from ashes,[270] or use the ashes as substitute for other materials.[271] It is shown that it is possible to extract phosphorous,[272] zinc[273] and copper[274] from MSWIFA in Sweden. Many stakeholders are also working on extracting salts,[275] mostly from MSWI fly ash.[276]

The Finnish Forest Engineers Association estimates an annual production of 650,000 tons of bio ash in Finland.[277] Ash from Finnish pulp industry is quite

265. Søråsen et al. Kildekarakterisering av askeavfall fra forbrenningsanlegg. Norske Skog.
266. Ebert et al. Screening of untreated MSWI fly ash for use in cement-based materials: chem. and ph. PSN Appl. Sc. 2020.
267. Kirkelund et al. Greenlandic MSWIFA and MSWIBA as secondary resource in Mortar.: Int. J. Sus. Dev. Plann, 2016.
268. Kirkelund, G. Ch. of MSWIBA for pot. use as a subbase in Greenlandic road construction. Tech. Uni. of Denmark 2012.
269. Lima et al. Screening dilute sources of rare earth elements for their circular recovery. J. of Geochemical Exploration 2022.
270. Seres, S. Resource recovery from MSW fly ash. M.Th. Umeå University 2018.
271. Hanson, L. Characterization of bottom ash from MSWI as a possible element in concrete. M.Th. Chalmers 2017.
272. Kalmykova et al. Phosphorus recovery from municipal solid waste incineration fly ash. Waste Management 2013.
273. Fedje et al. Zinc recovery from Waste-to-Energy fly ash – A pilot test study. Waste Management 2020.
274. Tang, J. Removal and Recovery of Metals from MSWI Ashes by a Hydrometallurgical Process. PhD.Th. Chalmers 2017.
275. Johansson, K. LCA of tr. proc. for FA from MSWI – A comp. of the Ash2Salt process and existing tr. meth. SLU 2017.
276. Nedkvitne et al. Variation in chemical composition of MSWI fly ash and dry scrubber residues. Waste Management 2021.
277. www.puunjalostusinsinoorit.fi/en/about-pi/

interesting as an industrial large bio ash resource,[278] because it has a different composition than the other Nordic countries.[279] This is 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,[280] numbers that include several very different sources.

It has been more difficult to find the correct numbers for Denmark. Denmark has converted its coal fired power stations into biomass power stations, generating ash that is mostly used in the concrete sector. Some ash is reused as fertilizer,[281][282][283] while most is used in the cement sector.[284][285] With a combined consumption of appr. 20 million tons of biomass and an average ash content of 6% - we estimate the Danish ash production to be 1,2 million tons. In the autonomous territories, there are some use of biomass generating ash. Most important is the generation of appr. 1000 tons of ash on Åland.

Rubidium is not regarded as critical by EU, but by USA, Russia and Japan. If EU is reconsidering its opinion, it is good to know that scientists from Finland has developed technology to extract rubidium from their wood/peat incineration ash. If necessary, Finland could easily supply the global need of rubidium from this circular source.[286]

In the aggregation of data of CRM volumes in Nordic ashes, we have found good data for CRMs in MSWIBA[287] and MSWIA[288] in Sweden. We also have waste incineration and residue data from Greenland.[289] There are work ongoing for increased recovery from incineration ashes in Denmark.[290] Sweden have done a lot of research on both ashes from MSWI[291] and biomaterials.[292] There are much less data from Norway.[293]

We have also looked at some reports from neighbouring countries, where the data could supplement Nordic data on minor metals.[294][295][296][297] Studies in UK have found levels of gold and PGM in incineration ash and sewage sludge ash similar to

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278. Oksanen et al. Fertiliser prop. of wastewater sludge and sludge ash–a case st. from the Finnish forest ind. E.Ch.EngS. 2023
279. Pöykiö et al. Heavy metals leaching in BA and FA fractions from ind.-scale BFB-boiler for ERA. Tr.NFe Met. Soc. China 2016
280. Nordic Council of Ministers. BAT for combustion and incineration residues in a Circular Economy.
281. Sørheim et al. Aske til oppgradering av biogass og som gjødsel. Bioforsk, 2015.
282. Hanssen, K.H. Tilbakeføring av treaske til skog. Norsk Institutt for Skog og Landskap, 2014.
283. Maresca et al. Recirculation of biomass ashes onto forest soils: Ash comp., mineralogy and leaching properties. DTU 2017
284. Astrup et al. Treatment and reuse of incineration bottom ash. Book 2016.
285. Maresca et al. LCA of air-pollution-control res. from WI in Europe: Imp. of comp. tech. and long-term leaching. WM 2022.
286. Nygren, Enni. Recovery of Rubidium from Power Plant Fly Ash. Dissertation 2019.
287. Engfeldt, C. Aska från energiproduktion – producerad och använd mängd aska i Sverige 2006. Svenska Energiaskor, 2007.
288. Johansson et al. Kritiska metaller i svenska avfallsaskor. SP Sveriges Tekniska Forskningsinstitut 2013.
289. https://global-recycling.info/archives/5971
290. Allegrini, E. Resource recovery from waste incineration residues. PhD Thesis 2014. DTU Denmark.
291. Hedenstedt et al. Korrosion vid lagring av slagg från avfallsförbränning Energiforsk 2016.
292. Alankangas et al. Kartläggning av restprodukter för efterbehandling og inhibering av gruvavfall. 2014.
293. Kessel, J. Recovery of Zinc from Municipal Solid Waste Fly Ash. M.Th. University of Oslo 2018.
294. Maldonado-Alameda, A. Environmental potential assessment of MSWI bottom ash-based. J. of haz waste 2021.
295. Pérez-Martínez, S. Ch. and partition of val. metals from WEEE in weathered MSWIBA, with a view to recovering. JoClProd.
296. Kasina, M. Ass. of Val. and Critical Elements Rec. Pot. in Ashes from Proc. of MSW and Sewage Sludge Th. Treat. Res.2020.
297. Voisniene et al. Effect of MSWI FA on the properties, microstructure and durability of clay bricks. Ceramics-Silikáty (2020)

some low-grade ores currently mined.[298] MSWI BA in Denmark also have analysed precious metals.[299]

As there will be consistent large volumes of ashes available for many years to come, research and incentives should be made to stimulate increased recovery of CRMs, and other beneficial elements. We will look deeper into these possibilities in phase 2 of this project.

298.Prichard et al. Precious metals in urban waste. Water and Environment Journal 30 (2016)
299.Clausen et al. Ch. of IBA from a Danish WtE plant: a step towards closing the material cycle. GEUS Bulletin 2019.

Appendix 4 Collection and sorting of waste in the Nordics

Collection and sorting of CRM-waste in Norway

Most Norwegian waste is collected by companies operating in a free market. Collection and preparation of Norwegian waste streams for recycling is dominated by a few large companies that both operate their own transport fleet and temporary waste storage and pre-treatment plants. These companies include Norsk Gjenvinning, Franzefoss Gjenvinning, Ragnsells and Stena Recycling. They operate plants for sorting, shredding, and other pretreatment before final recycling operations or other end treatments.

Collection of municipal and household waste

Norway is organized into 356 municipalities that are responsible for the collection and treatment of household waste. This responsibility is detailed in the waste regulation and allows the municipalities to charge its citizens a fee to cover this service. The regulation prohibits this fee from exceeding the actual treatment costs of the collected waste as a way of subsidizing other waste management efforts and must keep separate accounts on statutory waste treatment compared to other waste treatment.

Norwegian municipalities organize waste collection in very different ways when it comes to the number of waste categories collected, what type of collection system is used, and whether the collection takes place in collaboration with other municipalities or not. There are also large differences regarding whether the collection is performed by the municipality themselves, or if the services are bought as a service. Many municipalities have organized common waste treatment services in an inter-municipal enterprise.

Examples of waste categories that are collected separately in many municipalities include paper/cardboard, organic waste, plastic, glass and hazardous waste. The collection is typically performed through the use of containers, and plastic bags. In densely populated areas buried containers for several households are increasingly applied.

EPR-schemes in Norway

The collection and treatment of some waste streams are regulated by extended producer responsibility agreements (EPR). Norwegian EPR systems exist for packaging, WEE, batteries, vehicles, tires, and PCB-containing windows.

Table A11 EPR schemes approved by the Norwegian Directorate of the Envionment

Approved return company	Product
AS Batteriretur	Batteries
Autoretur AS	Vehicles
ERP Norway AS	Batteries, WEE
Grønt Punkt Norge AS	Packaging
Norsirk AS	Batteries, WEE, Packaging
Norsk dekkretur AS	Tires
Recipo AS	Electronics
Renas AS	Batteries, WEE
Serva AS	Batteries

Collection and sorting of CRM-waste in Sweden

Collection of municipal and household waste

In Sweden, household waste is defined as "waste from households and waste similar to household waste". (Nordic Report, 2016)

In Sweden, each municipality (290 municipalities) is responsible for the collection, transportation, recycling, and disposal of municipal waste, as mandated by Chapter 15 of the Environmental Act, Section 3. Additionally, waste under municipal jurisdiction falls under Chapter 15, Section 20 of the same act. Municipalities have significant flexibility in shaping their waste regulations and systems to ensure environmentally and health-friendly waste management. The regulations specify collection intervals for different areas and waste fractions. To finance waste management through fees, the municipal council must approve a waste tariff. Typically, waste collection occurs at property boundaries. Material recycling of household waste primarily occurs through the collection at recycling centres, recycling stations, and near-property collection.[300] The municipalities are responsible for transporting municipal waste to a treatment plant for recycling or disposal, including waste from households and similar waste from establishments like restaurants, shops, and offices.[301]

Municipal waste is managed jointly by municipalities and producers. Municipalities cover their costs through waste fees, while producers incur charges as a product fee. The municipal council determines municipal waste fees, while producers have control over the product fee's size.[302]

Swedish municipalities can choose how to organize their waste management, in line with the principle of local autonomy enshrined in the constitution. As of 2021, there were 55 wholly-owned municipal companies engaged in waste management. A little over one-third of municipalities handle the collection of food and residual waste in-house, using their own vehicles and staff. In two-thirds of cases, collection is outsourced through procurement. Waste treatment is either done by municipalities themselves or by external contractors through procurement, which can include other municipalities, other municipal companies, or private companies.[303]

In 2022, Sweden collected and processed 4.7 million tons of household waste from households and businesses. This resulted in each Swedish resident generating 449 kg of household waste, a 5% reduction from 2021.[304]

Households in Sweden are obligated to separate recyclable materials such as paper, packaging, electronic waste, batteries, and bulky items. These materials must be deposited in the designated collection systems.[305]

Waste separation practices can vary from place to place. For instance, food scraps and other organic waste are often collected separately for energy recovery and nutrient recycling, with specific rules depending on the treatment process.[306]

In newly built Swedish homes, designated spaces for waste sorting bins are required. Smaller apartments are recommended to have two sorting bins of at least 20 litres in the kitchen and two additional units for flexible placement. Larger apartments should provide a capacity of 30 litres in the kitchen and four extra units for flexible placement. One of the sorting bins must be allocated for food waste, though the exact design may differ based on the local waste sorting regulations in each municipality.[307]

300.https://www.avfallsverige.se/fakta-statistik/kommunalt-ansvar/
301.https://www.sopor.nu/en/facts-about-waste-management/who-does-what-in-swedish-waste-management/municipalities-and-other-authorities/
302.https://www.avfallsverige.se/fakta-statistik/kommunalt-ansvar/ekonomi-och-styrmedel/
303.https://www.avfallsverige.se/fakta-statistik/kommunalt-ansvar/ekonomi-och-styrmedel/organisation-och-samverkan/
304.https://www.avfallsverige.se/fakta-statistik/avfallsstatistik/hushallsavfall/
305.https://www.sopor.nu/en/facts-about-waste-management/who-does-what-in-swedish-waste-management/households/
306.https://www.sopor.nu/en/sort-recycle/food-waste/
307.https://avfallsbransjen.no/2021/06/11/nye-krav-til-kildesortering-i-boliger-i-sverige/

EPR-schemes in Sweden

Sweden enforces producer responsibility for various waste types: packaging, electrical and electronic waste, and batteries in the context of municipal waste management.

Packaging

In 1994, producer responsibility for packaging (including newspapers) was introduced, mandating producers to manage collection and recycling. They established around 5,800 unmanned recycling stations nationwide with containers for different materials. Besides these stations, partnerships between municipalities, property owners, and producers created collection systems near properties. Currently, property-based collection covers 60% of multi-unit residences and under 25% of single-family households.

Starting in 2024, municipalities will assume packaging collection duties, and by 2027, property-based collection will become the primary system for all households and co-located businesses. Producers will remain responsible for recycling and cost coverage, aiming to enhance accessibility and boost recycling.

Electrical Waste and Batteries

Producer responsibility for electrical and electronic products in Sweden led to collaboration between municipalities and producers for waste collection. Organizations like Avfall Sverige, Sveriges Kommuner och Landsting, and El-Kretsen work together through the El-return system. Municipalities collect electrical waste from households while producers manage processing. El-Kretsen collaborates with Recipo, representing producers.

Advancements in recycling technology have made it easier for consumers to participate. For example, consumers can place all small light sources in the same container. Many places, such as galleries and grocery stores, have larger collection bins for smaller electrical waste and light bulbs.

Battery producers are responsible for collecting, processing, and recycling all batteries, regardless of when they entered the market. In roughly 70% of municipalities, El-Kretsen manages portable battery collection, while other municipalities handle collection for a predetermined fee from producers.[308]

The Swedish Environmental Protection Agency (Miljødirektoratet i Sverige: Naturvårdsverket) coordinates environmental efforts in Sweden, overseeing climate, air quality, biodiversity, and more.[309]

308.https://www.avfallsverige.se/fakta-statistik/insamling/kommunalt-avfall-under-producentansvar/
309.https://www.naturvardsverket.se/vagledning-och-stod/producentansvar/producentansvar-for-forpackningar/

Collection and sorting of CRM-waste in Denmark

Collection of municipal and household waste

Denmark's waste management involves municipalities, joint waste companies, public and private sectors, and government policies. The country consists of 98 municipalities.[310] The collection of household and municipal waste faces challenges due to heavy government investment in waste incineration, leading to a surplus of waste and limited recycling facilities. Municipalities own most incineration plants, surpassing waste generation capacity.[311]

In the absence of specific requirements outlined in the Statutory Order on Waste, local authorities enjoy autonomy in determining their waste handling and disposal approaches. While some major local authorities opt to manage and process waste independently, the majority have established collaborative waste management companies. Hazardous waste disposal plants and landfill sites are overseen by public authorities. Household waste collection is often outsourced to private contractors, who often also oversee the collection of industrial waste. Additionally, private contractors actively participate in managing and processing waste for recycling purposes.[312]

A new waste reform, effective since July 2021, mandated a requirement for municipalities to establish separate waste collection services.[313] The reform mandates municipalities to collect ten waste fractions from households, including food, paper, cardboard, metal, glass, plastic, textile waste, beverage and food cartons, residual waste, and hazardous waste. These requirements took effect on July 1, 2021, with textile waste becoming effective in 2022. Municipalities are also required to label waste containers using a common pictogram system developed by the Danish Waste Association, which Norway has adopted as well.[314]

In 2020, Denmark generated around 5 million tons of municipal waste, with a high per capita rate of 845 kg, a recycling rate of 53.9%, incineration at 45.2%, and less than 1% sent to landfills.[315] Denmark's waste management adheres to national regulations like the Environmental Protection Act and the Statutory Order on Waste.[316]

310. https://www.star.dk/en/about-the-danish-agency-for-labour-market-and-recruitment/municipalities/
311. https://www.oecd-ilibrary.org/sites/d1eaaba4-en/index.html?itemId=/content/component/d1eaaba4-en
312. https://dakofa.com/element/test-article-today/
313. https://www.retsinformation.dk/eli/retsinfo/2022/9792
314. https://avfallnorge.no/bransjen/nyheter/danmark-stromlinjer-avfallsinnsamlingen
315. https://mst.dk/publikationer/2023/oktober/affaldsstatistik-2021
316. Early warning assessment related to the 2025 targets for municipal waste and packaging waste

EPR-schemes in Denmark

Denmark has instituted producer responsibility schemes covering electronics, batteries, and vehicles. Additionally, voluntary take-back programs are in place, and efforts are underway to expand existing schemes and introduce new ones. The timeline for producer responsibility implementation is as follows: starting in 2023 for tobacco product filters and in 2025 for packaging materials.[317]

Electronics [318]

For electronics, producers or importers must adhere to specific regulations in Denmark. This includes:

1. Labelling electronic products in accordance with relevant regulations, including the use of pictograms.
2. Collecting electronic waste either directly or through agreements with waste collection entities.
3. Ensuring environmentally approved treatment of collected electronic waste.
4. Register your business in the national producer registry and report annual quantities of electronics sold and electronic waste collected.

Producers can either fulfil these responsibilities individually or participate in collective compliance arrangements. Collective schemes in Denmark vary in organization and focus based on the type of electrical and electronic equipment being marketed.

Batteries [319]

For batteries, producers and importers must comply with the following rules in Denmark:

1. Label batteries according to applicable regulations, including pictograms and capacity labelling for portable and automotive batteries.
2. Create sales and information materials.
3. Conduct awareness campaigns about the collection of portable batteries.
4. Register your business in the producer registry.
5. Report quantities of portable batteries marketed in Denmark annually to SKAT and contribute to municipal collection fees.
6. Report quantities of automotive and industrial batteries marketed in Denmark annually to the producer registry.
7. Report collected and processed quantities of portable batteries to the producer registry.

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317. https://producentansvar.dk/en/products-and-responsibility/legislation/
318. https://mst.dk/erhverv/groen-produktion-og-affald/affald-og-genanvendelse/producentansvar-for-affald/elektronik-og-producentansvar
319. https://mst.dk/erhverv/groen-produktion-og-affald/affald-og-genanvendelse/producentansvar-for-affald/batterier-og-producentansvar

8. Collect batteries either directly or through agreements with waste collection entities.
9. Ensure environmentally approved waste treatment for collected batteries.

There is a nominal fee for registration and reporting, often handled through collective schemes.

Battery categories covered include

1. Portable batteries (single-use or rechargeable, including accumulators).
2. Automotive batteries (lead accumulators used as starting batteries for combustion engine vehicles).
3. Industrial batteries (accumulators, including those used in electric vehicles and e-bikes).

These regulations are based on EU directives (Battery Directive) and have been incorporated into Danish law through two notifications and an EU regulation.

Vehicles [320]

Producer responsibility for both new and used cars has been in effect in Denmark since 2007. In practical terms, this means that manufacturers and importers of new and used cars, whether passenger or commercial vehicles, must ensure that all vehicle owners can dispose of their end-of-life vehicles anywhere in the country without incurring disposal fees.

Vehicle owners can confidently deliver their scrap cars to approved dismantlers with whom the vehicle importers have agreements. In Denmark, producer responsibility is supplemented by a scrapping refund system, where 2200 DKK is paid when a scrap car is delivered to an authorized dismantler. The right to return free of charge applies to all vehicles, regardless of their age. Payment of the scrapping refund applies to passenger and commercial vehicles registered in Denmark after July 1, 2000.

Furthermore, Danish importers of new and used passenger and commercial vehicles must be registered in a producer registry to market their vehicles in Denmark legally. The registry is administered by the Danish Producer Responsibility (DPA), and an annual fee is required for registration.

Danish Producer Responsibility (DPA) carries out a number of administrative tasks for the existing extended producer responsibility and the scrapping compensation scheme on behalf of the Danish Environmental Protection Agency (MST). DPA is an independent non-profit organization that was established in 2005 by the business community organizations as part of the Danish implementation of producer responsibility.

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320. https://mst.dk/erhverv/groen-produktion-og-affald/affald-og-genanvendelse/producentansvar-for-affald/biler-og-producentansvar

Table A12 Danish Producer Responsibility Organisations

Approved return company	Product
Bilretur v. Stena Recycling	Vehicles (only cars)
Elretur	WEE
Emballageretur	Packaging
ERP Denmark	Packaging
Recipo ApS	WEE, Batteries
RENE AG	WEEE, Batteries, Packaging
ReturBat	Lead batteries
VANA - Dansk Emballageansvar	Packaging

Collection and sorting of CRM-waste in Finland

Collection of municipal and household waste

Finland defines household waste as "waste generated in permanent dwellings, holiday homes, residential homes and other forms of dwelling, including sludge in cesspools and septic tanks, as well as waste comparable in its nature to household waste generated by administrative, service, business and industrial activities. (Nordic report)

In Finland, municipal waste from households is the responsibility of the country's numerous municipalities. They've streamlined waste management through 39 inter-municipal associations, enhancing infrastructure over the past two decades.[321]

Waste sorting is meticulous in Finland. Materials like paper, cardboard, glass packaging, metal, plastic, bio waste, mixed waste, hazardous waste, electrical equipment, and batteries are usually sorted separately. Housing complexes provide sorting containers for various waste types, and biowaste is converted into compost or biogas, used for heat and electricity.[322]

321. Municipal waste management in Finland: https://www.eea.europa.eu/publications/managing-municipal-solid-waste/finland-municipal-waste-management
322. https://www.infofinland.fi/en/housing/waste-and-recycling

Finland's commitment to a circular economy led to comprehensive regulations. Municipalities are primarily accountable for household waste, and property owners, waste holders, and housing companies must establish waste collection points. Residents are required to use these points for depositing their waste. Inhabitants of detached houses usually collect mixed waste, but the new waste legislation will require biowaste separation in densely populated areas. Other waste types can be delivered to sorting stations or collection points organized by producers. Hazardous waste is accepted free of charge at specified collection points, while medical waste should be taken to pharmacies.[323]

In Finland there are some instances of free competition in the market for the collection of household waste, i.e. if the waste collection is organised by property holders and not the municipality.

EPR-schemes in Finland

In Finland, producer responsibility (EPR) extends to various product categories, including[324]:

- Accumulators and batteries (including those in vehicles and electronic devices).
- Passenger, cargo, and recreational vehicles.
- Packaging.
    - For packaging, producers and importers with a net revenue exceeding EUR 1 million must manage the waste from packaging materials they place on the market. They can do so by either joining a Producer Responsibility Organization (PRO), handling the treatment themselves (by reporting to the ELY Centre of Pirkanmaa), or establishing a PRO in collaboration with other packaging producers.
- Paper and paper products.
- Tires.
- Electrical and electronic equipment.

The ELY Centre of Pirkanmaa oversees producer responsibility compliance nationally, except for Åland, where the Government of Åland assumes this role. ELY compiles official packaging statistics, including quantities, reuse, and recycling rates based on data reported by RINKI and other organizations. Note that these statistics do not encompass packaging from passenger imports, foreign online shopping, producers or importers with a turnover of less than EUR 1 million, or Åland's figures.

323. https://gnf.fi/wp-content/uploads/2022/12/Overview-of-municipal-solid-waste-management-in-Finland_FINAL.pdf
324. https://www.ymparisto.fi/fi/luvat-ja-velvoitteet/tuottajavastuu

While waste from foreign online sales was initially excluded from the EPR system, producers are now required to collect such waste. The new Waste Act (Government of Finland, 2021) introduces measures to regulate online sales:

- Foreign online sellers must meet EPR obligations, similar to Finnish producers.
- Marketplace operators can help fulfil EPR requirements.
- Other foreign operators with producer-like roles can join the EPR scheme.

For PRO compliance, there are five accepted PROs for packaging in Finland, covering various materials such as metals, wood, glass, fibre packaging, and plastic. These PROs collaborate through Finnish Packaging Recycling RINKI Ltd, which coordinates the execution of producer responsibility for packaging. The scope of EPR is set to encompass all packaging materials in the future, as per the revised Waste Act.

Table A13 Finnish Return companies
Miljødirektorat: Ymparisto https://www.ymparisto.fi/en/permits-and-obligations

Approved return company	Product
Finnish Packaging Producers Ltd	Packaging
Sumi Oy	Packaging

Collection and sorting of CRM-waste in Iceland

Collection of municipal and household waste

Waste management in Iceland has evolved significantly in recent years. Before 1990, waste disposal mainly involved open pit burning and landfilling. Today, regulations govern incineration and landfill sites in compliance with EU standards. However, compared to Nordic and EU-27 nations, Iceland lags behind in reducing landfill rates and increasing energy recovery and recycling rates. The EU landfill directive sets a target for municipal solid waste (MSW) landfilled to be under 10% by 2035, but currently, it stands at over 60%. In 2019, Iceland generated approximately 237,000 tons of MSW, with 61% (about 144,000 tons) either landfilled or incinerated, including 3,100 tons exported for energy recovery abroad. The remaining 39% was recycled or reused.[325]

325.Waste management in Iceland: Challenges and costs related to achieving the EU municipal solid waste targets, 2022

In Iceland, local authorities determine household and industrial waste collection arrangements and adopt regional waste treatment plans. The Minister of the Environment, Energy, and Climate sets national waste treatment policy, while the Environment Agency enforces waste treatment legislation. Waste treatment fees are imposed on various product categories to ensure waste producers cover treatment costs, with the Icelandic Recycling Fund managing fee administration. [326]

Despite progress, Iceland's six capital municipalities have previously not recycled household organic waste, and their waste management systems have varied. It has been planned to establish a unified household waste management system, including organic waste collection, by spring 2023. This change allows households to separate four waste types: paper and cardboard, plastic, biowaste, and general waste. Currently, paper and cardboard are the main recyclables. Collection points for other materials, such as metals, textiles, glass, and return packaging, will also expand. Iceland has faced challenges in recycling plastic waste and had to export some to Sweden. The GAJA biogas and composting plant, opened in 2020, aimed to produce soil and biogas but faced controversy due to high plastic content.[327]

Local authorities are responsible for waste collection and waste management arrangements, including the operation of waste reception and collection centres. They also announce waste management aspects in official publications. They often grant permits for landfill operation and waste reception, providing information to the Environment Agency. Stricter rules for separate household waste collection will come into effect from January 1, 2023, with uniform labelling for specific waste categories. The main rule is that certain waste categories must be collected in separate containers at specified locations. Until January 1, 2023, a fixed fee per property unit, based on waste quantity, type, or other factors, is permitted. Afterward, waste management fees will follow a "Pay as you throw away" methodology, considering waste quantity, type, collection frequency, landfilling, and other cost-influencing factors. Up to 25% of a municipality's total costs can still be collected as a fixed fee. In the first two years after implementing these requirements, until January 1, 2025, this percentage may be up to 50%.[328]

EPR-schemes in Iceland

The implementation of the Act on Recycling Fees in Iceland aimed to accomplish several key goals. Its primary purpose was to entrust the Icelandic Recycling Fund with the task of creating favourable economic conditions to encourage reuse and recovery, decrease the amount of waste ending up in final disposal, and ensure the proper management of hazardous substances. Operating as an extended producer responsibility (EPR) scheme, the fund utilizes economic incentives to establish

326. https://www.government.is/topics/environment-climate-and-nature-protection/waste-treatment-/
327. http://www.nordiclabourjournal.org/nyheter/news-2022/article.2022-02-22.3563437815
328. https://urgangur.is/a-new-law-on-waste-takes-effect-in-2023-what-will-change/

practical waste processing arrangements. Producers and importers are obligated to pay recycling fees for various categories of products, including motor vehicle waste, paper packaging, plastic packaging, tires, bale plastic, hazardous waste, and WEEE. These fees are assessed based on the specific category and can range from ISK 3 to ISK 900 per kilogram (as of 2013).[329]

Iceland's approach differs from that of other EU Member States. Upon importing a product, an automatic notification is sent to the Icelandic Recycling Fund. Consequently, the producer becomes registered with the Environment Agency. To initiate this process, importers must first register with the Customs Authority, while local manufacturers are required to register with the Internal Revenue department. Subsequently, the Icelandic Recycling Fund charges the producer a take-back and recycling fee, assuming both producer responsibility and the responsibility for reporting to the Environment Agency.[330]

Collection and sorting of CRM-waste other autonomic territories in the Nordics

Collection of municipal and household waste

Greenland

In Greenland, the municipalities, bear the responsibility for the efficient collection and treatment of municipal waste. An environmentally conscious approach has led to the practice of maximizing waste incineration for heat production within Greenland, rather than transporting it across the Atlantic. Electronic and hazardous waste is carefully shipped to Denmark, where facilities ensure proper dismantling of electronic waste and secure storage of hazardous materials for subsequent shipping. Notably, one municipality has implemented a collection system for glass packaging, which is crushed and repurposed in asphalt production. Moreover, in all municipalities, bulky waste is meticulously sorted for direct reuse. In three specific local municipalities, innovative schemes or pilot programs are in place to promote the recycling or reuse of various materials, including glass, metal, wood, paper, cardboard, food waste, and items suitable for direct reuse.[331]

Faroe Islands

The Faroe Islands operate two distinct waste management systems, one managed by Tórshavn municipality, known as Kommunala Brennistøðin, and the other by an inter-municipal company called IRF, responsible for handling waste from the remaining 28 municipalities. Each entity maintains its own incinerator, alongside landfills designated for non-combustible waste such as asbestos. The waste sorting process involves the use of white bags or green bins for paper and cardboard, red

329. https://expra.eu/countries/iceland/
330. https://erp-recycling.org/en-it/whats-up/events/2019/07/iceland-erp-system-updated/
331. https://global-recycling.info/archives/5971

bags for hazardous waste, and containers for other non-hazardous or non-recyclable materials, which often include food waste and plastic packaging. Additionally, IRF's hazardous waste collection includes items like lightbulbs, batteries, and small electronics.[332]

Åland Islands

In Åland, waste management adheres to the regulations outlined in the Act of Waste, ÅFS 1981:3 (a copy of the Finnish law), which defines household waste to encompass waste generated by both households and similar waste produced by businesses. The municipalities of Åland bear the responsibility for managing private household waste. Waste management services are efficiently handled by MISE (Ålands Miljöservice). In households throughout the Åland Islands, an effective recycling system is in place for materials such as glass, milk cartons, cardboard, metal, aluminium, plastics, compost, and flammable materials.[333]

EPR-schemes in Greenland, Faroe Island and Åland

Greenland

Greenland, as a non-member of the EU, follows its own path with a slight delay compared to the rest of the world. It draws inspiration from Denmark and the EU but takes more time to establish economically viable systems. Products are exempt from producer responsibility when introduced to Greenland.[334]

Åland Islands

On recycling stations in Åland, only combustible residual waste and separately sorted metal and glass are currently accepted. Other recyclable materials such as paper, plastic, and cardboard are directed either to producer-led collection systems or included in the municipal waste management for energy recovery. For the time being, paper and cardboard are still separately collected outside the Listersby recycling centre for some form of recycling. The reasons for this reduction in the number of recyclable fractions are both economic and environmental. The lack of a functioning producer responsibility system in Åland means there are no economic or legal prerequisites for handling separately sorted waste in a manner compliant with the law and environmentally sound. In practice, there is no effective producer responsibility in Åland of the kind mandated by the EU, especially in relation to recyclable packaging waste. There is no system established and funded by producers for waste collection. Therefore, municipalities lack the conditions to participate in the collection of such waste for recycling until producers address this issue.

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332. https://www.diva-portal.org/smash/get/diva2:1604003/FULLTEXT01.pdf
333. http://norden.diva-portal.org/smash/get/diva2:721027/FULLTEXT01.pdf
334. https://www.hvidvare-nyt.dk/ude-af-sind-groenland-producentansvar-nuuk-bydger-oestgroenland-dumpen-kulusik-ittoqqortoormiit/

Overview of the EPR schemes in the Nordic countries [335]

Table A14 Overview of the EPR schemes in the Nordic countries

	WEE	BAT	ELV	Packag-ing	Disposable drink containers	Tyres	Graphic paper	Medical waste	Agri-cultural film
Norway	X	X	X	X	X	X			
Denmark	X	X	X		X	X			
Sweden	X	X	X	X	X	X	X	X	X
Finland	X	X	X	X	X	X	X		
Iceland	X	X	X	X	X	X		X	X
Greenland				X	X	X	X		
Faroe Islands	X			X					

335.Nordic report, p. 111, 2016

Table A15 The legal framework of waste management in the Nordic countries – Definitions and extent of competition (from the Nordic report 2016)

	Definition of household/municipal waste	The extent of municipal exclusive position	Definition of household/municipal waste
Denmark	Waste is defined by source rather than form. Household waste is defined as waste gene rated by households, e.g. domestic waste, garden waste.	Municipalities have an exclusive position regarding the collection of all household waste and the collection of commercial waste to incineration and landfills. In buildings with a mix of undertakings and residents, companies can acquire the services from municipalities.	There is competition in the collection of commercial and industrial recyclable waste. The collection of house hold waste, combustible and landfillable waste from commercial undertakings is in many cases procured by municipalities from private undertakings.
Faroe Islands	There is a clear distinction between house hold and commercial/industrial waste. Municipal Solid Waste (MSW) is sub categorised by national laws and regulations.	IRF and KBR, the municipal undertakings, are tasked with all waste management in the Faroe Islands, i.e. both house hold and commercial waste.	There is some competition in respect of the manage ment of scrap metal. IRF and KBR, the munici pal undertakings, can also procure a part of the servi ces from private under takings.
Finland	Household waste is defined as "Waste generated in permanent dwellings, holiday homes, residential homes and other forms of dwelling, including sludge in cesspools and septic tanks, as well as waste compa rable in its nature to household waste generated by admini strative, service, busi ness and industrial activities."	The municipal exclusive position extends to household and similar waste as defined by legislation. The municipality may decide that property holders are responsible to organise the collection of household waste. Even in these cases the munici pality decides how the waste is disposed of. If the municipalities decide to organise the collection themselves, they always procure these services.	There is free competition in the collection and manage ment of waste other than household waste, as defined by law. There is free competition for the collection of house hold waste in municipalities where the waste collection is organised by property holders and not the municipality. In some cases the municipalities or their undertakings procure a part of the service, e.g. collection of household waste.

Greenland	Each municipality decides how waste is defined within its area. Most municipalities differentiate between the collection of dome stic waste and waste from industrial and commercial facilities.	The municipalities can opt for having in-house waste management services.	In some cases, in larger settlements the waste collection is outsourced to private undertakings. In smaller settlements the service is usually provided by the municipalities them selves. All waste facilities i.e. waste transfer stations, incinerators and landfills are owned and operated by municipalities.
Iceland	Waste is defined by its source rather than form. Household waste is defined as waste from households, e.g. glass, paper, cardboard, plastics, etc.	The municipalities' exclu sive rights extend to the collection of waste from households. The munici palities also control that waste stream. Some EPR waste from households may not be collected by municipalities kerbside, e.g. batteries, disposable drink contain ners, hazardous waste, etc.	There is free competition in the collection and further management of comercial and industrial waste. Municipalities also procure collection services for household waste in most instances. Whether or not further management, e.g. sorting is a part of the procured service depends on the terms of the procurement contract.
Norway	Waste is defined by source, rather than form. Household waste is defined as waste from households. Any waste from non household premises is the responsibility of the undertaking producing the waste. The municipality must monitor that waste emanating from industries which is similar to household waste is properly collected, and that the relevant regulations are adhered to.	The task of collecting and sorting household waste has historically been a public task in Norway and it is still the municipalities' exclusive right pursuant to Section 34 of the Pollution Control Act.	There is free competition in the collection and further management of industrial and commercial waste from undertakings. Some municipal or inter municipal waste manage ment undertakings procure a part of the services from private undertakings. In some cases municipalities procure the services directly from public or private undertakings.

Abbreviations

Al	Aluminium	**Sb**	Antimony
As	Arsenic	**SBR**	Synthetic Rubber (Styrene-butadiene-rubber)
B	Boron	**Sc**	Scandium
Be	Beryllium	**Si**	Silicon
BF	Blast Furnace	**Sm**	Samarium
BRICS	Brasil, Russia, India, China, South Africa	**SME**	Small and Medium sized Enterprises
C	Carbon	**Ta**	Tantalum
Ce	Cerium	**Tb**	Terbium
Co	Cobalt	**Ti**	Titanium
CRM	Critical Raw Material	**Tm**	Thulium
CRMA	Critical Raw Material Act	**V**	Vanadium
Cu	Copper	**W**	Tungsten
Dy	Dysprosium	**W2E**	Waste to energy
EAF	Electric Arch Furnace	**WEEE**	Electric and electronic waste
EE	Electric and electronic	**Yb**	Ytterbium
EEA	European Economic Area	**Y**	Ytrium
EEC	European Economic Community	**Zr**	Zirconium
EIB	European Investment Bank	**Lu**	Lutetium
EOL-RIR	End Of Life - Recycling Input Rate	**Mg**	Magnesium

EPR	Extended Producer Responsibility	**Mn**	Manganese
Er	Erbium	**Nb**	Niobium
Eu	Europium	**Nd**	Neodymium
EVE	Electric Vehicle	**Ni**	Nickel
F	Fluorine	**NIB**	Neodymium Iron Boron magnet
Ga	Gallium	**P**	Phosphorous
Gd	Gadolinium	**Pd**	Palladium
Ge	Germanium	**PCB**	Printed Circuit Board
He	Helium	**PGM**	Platinum Group Elements
Ho	Holmium	**ppm**	parts per million
HREE	Heavy Rare Earth Elements	**Pr**	Praesodymium
ICE	Internal Combustion Engine	**Pt**	Plantinum
Ir	Iridium	**Re**	Rhenium
La	Lanthanum	**REE**	Rare Earth Elements
Li	Lithium	**Rh**	Rhodium
LREE	Light Rare Earth Elements	**Sb**	Antimony
Lu	Lutetium	**SBR**	Synthetic Rubber (Styrene-butadiene-rubber)
Mg	Magnesium	**Sc**	Scandium
Mn	Manganese	**Si**	Silicon
Nb	Niobium	**Sm**	Samarium
Nd	Neodymium	**SME**	Small and Medium sized Enterprises
Ni	Nickel	**SOFC**	Solid Oxide Fuel Cell

NIB	Neodymium Iron Boron magnet	**Ta**	Tantalum
P	Phosphorous	**Tb**	Terbium
Pd	Palladium	**Ti**	Titanium
PCB	Printed Circuit Board	**Tm**	Thulium
PGM	Platinum Group Elements	**V**	Vanadium
ppm	parts per million	**W**	Tungsten
Pr	Praesodymium	**W2E**	Waste to energy
Pt	Plantinum	**WEEE**	Electric and electronic waste
Re	Rhenium	**Yb**	Ytterbium
REE	Rare Earth Elements	**Y**	Ytrium
Rh	Rhodium	**Zr**	Zirconium

About this publication

Recycling of Critical Raw Materials in the Nordics

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