

Information Management and Classification

Secondary Resources and their
Critical Raw Material Potential
in the Nordic Countries

Information Management and Classification of Secondary Resources and their Critical Raw Material Potential in the Nordic Countries

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Table of contents

1	Executive summary	5
2	Introduction	7
2.1	Macro-economic factors influencing metal prices	8
2.2	Current outlook	11
2.2.1	Short-term commodity price stability	11
2.2.2	Long-term commodity price projections	13
2.2.3	Considerations of the impact of short-term price instabilities and long-term pricing models on CRM exploration and mining	14
2.3	The Nordic Sustainable Minerals Programme	16
2.4	Work package 2: Recovery & Recycling	16
2.5	Definition and significance of secondary resources in the context of recovery of co- and by-products	17
2.6	Importance of CRMs in the green energy transition	19
2.7	Metal's companionship	23
2.8	CRMs and non-CRMs considered important for trade in the Nordic countries	25
2.9	Mineral and metal production in the Nordic countries	29
2.9.1	Mining and mineral processing in Denmark and Greenland	29
2.9.2	Mining and mineral processing in Finland	30
2.9.3	Mining and mineral processing in Iceland	32
2.9.4	Mining and mineral processing in Norway	33
2.9.5	Mining and mineral processing in Sweden	34
3	Investigations of the CRM potential and other factors influencing waste management and re-mining in the Nordic countries	36
3.1	Environmental, social and governance issues associated with Finnish mine tailings	36
3.1.1	Aijala	38
3.1.2	Kaustinen	40
3.1.3	Otanmäki	41
3.1.4	Talvivaara	42
3.1.5	Project categorisation regarding public acceptance	44
3.1.6	Legal aspects related to the re-mining of tailings	44
3.1.7	Conclusions regarding the Finnish case studies	45
3.2	Grängesberg & Yxsjöberg case studies on tailings	46
3.2.1	Grängesberg	46
3.2.2	Yxsjöberg	46
3.2.3	Methods and sampling	47
3.2.4	Critical and strategic mineral potential of Grängesberg	50
3.2.5	Critical and strategic raw material potential of Yxsjöberg	51
3.3	Løkken case study on tailings	55
3.3.1	Ore geology	55
3.3.2	Mining and metal extraction history	55
3.3.3	Geochemical methodology	56
3.3.4	Geophysics	58
3.3.5	Results and discussion	60
3.3.6	Conclusions from the Løkken study	66

3.4	Building a dataset on mining waste in Norway	66
3.5	Extraction of metals from disposed mining sludge waters	67
3.5.1	Is there a more sustainable way to treat mine water?	67
3.5.2	Promising results in extracting metals at the lab scale	68
3.5.3	Pollution today – resource tomorrow?	70
3.6	Examination of aluminium dross from the Norðurál aluminium smelter at Grundartangi, SW Iceland	71
3.6.1	Introduction	71
3.6.3	Methodology	71
3.6.4	Results	71
3.6.5	Summary	73
3.7	CRM recovery potential of fly ash (FA) from Denmark	74
3.7.1	Purpose of the case studies	76
3.7.2	Municipal solid waste incineration (MSWI)	76
3.7.3	The two case studies and reference study	79
3.7.4	Waste composition	80
3.7.5	Sampling	82
3.7.6	Geochemical analysis	83
3.7.7	Boiler ash and filter ash – quantitative estimation	84
3.7.8	Results	85
4	The Nordic Database: integration of primary and secondary mineral resource data	89
4.1	A cloud-based repository for primary and secondary mineral resources in the Nordic countries	90
4.1.1	Workflows and methodology adopted and database organisation	91
4.2	Classification of primary and secondary resources	108
4.2.1	Methodology used for the economic valuation of ore deposits and mining waste	108
4.2.2	Application of the metal equivalent methodology to the Nordic Database	109
4.2.3	Classification results and implications for the primary and secondary CRM potential in the Nordics	112
5	Discussion and conclusions	117
6	Recommendations	124
	Annexes	126
	Annex A	126
	Annex B	129
	Annex C	130
	Annex D	131
	Annex E	132
	References	133

1 Executive summary

The management and classification of secondary resources represents an important step forward in promoting enhanced circularity. The reduction of knowledge gaps in mining waste characterisation, its inventorying and the development of appropriate waste classification schemes are treated in this contribution. These actions support circularity in mining practice. The objective is to provide a research tool/portfolio for the advancement and conceptualisation of the more sustainable handling of natural resources in the Nordic countries. This includes investigating attitudes and community perceptions regarding the potential exploitation of mining waste as a secondary resource.

A better understanding of the geographic distribution of mining waste, its characterisation and the definition of critical raw materials (CRMs) budgets, connected with the green energy transition (Eilu et al. 2021), can contribute to the dissemination of information pertaining to mining and industrial waste, and its potential re-mining or reuse. Another overarching objective is to guide future policy and decision making, enabling the responsible and sustainable use of natural resources. Decision makers require up-to-date knowledge and the ability to rapidly filter and understand where relevant information is stored.

According to the European Critical Raw Materials Act (CRMA, EU Commission 2023a), critical raw materials (CRMs) include those that are essential for the economy and have a high supply risk. Strategic raw materials (SRMs) are identified within this broader category and are crucial for strategic sectors and technologies such as green and digital transitions, defence and aerospace. Given this definition, this report uses the abbreviation CRM to include both non-strategic CRMs and CRMs that are considered SRMs. Thus, in this report, to simplify the reference to any CRM, we consider the abbreviations CRM and CSRM (critical and strategic raw materials) equivalent.

This report considers new methodological frameworks for the evaluation of the economic potential of CRMs in waste rock, tailings and other industrial processing waste (sludge and fly ash) in the Nordic countries. Multiple methodological approaches are documented throughout, from country-scale appraisals that capture mineral resources data into a database dedicated to Nordic mining waste to a series of case studies that focused on geochemical and geophysical investigations of secondary resources derived from mining and energy waste streams. Some of the results obtained, for instance at Grängesberg, Løkken and other sites in Sweden and Norway, respectively illustrate the importance of integrating geochemical and geophysical surveys to interpret the complexity of tailings ponds, improving the evaluation of mass and grade estimates of CRMs that were revealed to be significant. Additionally, environmental, social and governance issues were examined in four Finnish case studies, with public acceptance of tailings' re-mining assessed in two of them. Further to this, industrial mineral-metal processing facilities were investigated in Denmark and Iceland, providing a more comprehensive outlook of the CRM potential in the Nordics. These case studies, somewhat detached

from mining waste, are still rich in secondary resources and could become the main sources of CRMs with more in depth understanding of their value chains. In addition, the UNFC classification system was applied to the Otanmäki tailings in Finland and the Grängesberg and Yxsjöberg mining wastes in Sweden.

Other results of the database compilation showcase the need for more advanced geoinformation tools that should be capable of connecting the numerous dimensions of data gathered on primary and secondary mineral resources. These more advanced data representations can enhance the way we look at information, providing tools to filter and select information for decision making. They would also facilitate the interconnection with advanced analytics, emerging from applications that leverage artificial intelligence (AI)-based data classification and the more recent advancement of generative AI (Barbosa et al. 2024).

The Nordic PostgreSQL Database and its implementation resulted in a system that allows the rapid analysis of mineral deposit and (available) mining waste data. The use of criticality measures and heuristic methods and the extension of economic valuations based on the metal equivalent methodology provided filtered lists of primary ore and secondary resources, ordered by their importance as potential suppliers of CRMs. The classification workflow based on complex SQL queries demonstrated the advantage derived from the coupling of an SQL-capable platform with simple criticality and economic valuation systems. The level of data processing required in a web browser is minimal, facilitating decision-making processes.



2 Introduction

This introductory part of the report discusses key macroeconomic factors conditioning the demand and supply of commodities. By understanding demand and supply trends, it is possible to anticipate the needs of future economies and ultimately drive policy. With an appraisal of the current outlook of commodity prices, we provide some examples of short-term volatility and long-term commodity pricing projections that can explain why it is useful to consider and design data archives and applications that better define the value of mineral resources, including mining waste.

If we consider the strategy that the European Union (EU) is adopting to mitigate risk in the future supply of critical and strategic raw materials, what is clear is that it is considering the problem of potential shortages in mineral resources from different angles. One aspect is incentivising the current pipeline of mining projects that are going to produce some of the CRMs of concern (EU Commission 2020a, b, c, 2023a, IEA 2023). However, primary production is expected to take considerable time. The expected delay and inability to compete with producing nations (mainly China) has triggered the need for more urgent actions, and in this regard, the EU has recently formed commercial agreements with several countries that are considered rich in raw materials useful for the green energy transition (Guinea & Vanika 2023) with the objective of enabling the diversification of trade. A larger number of suppliers of CRMs would reduce supply chain risks and mitigate the likelihood of commodity price instability.

Furthermore, the EU Commission in the latest European Critical Raw Materials Act (CRMA) established benchmark targets to enhance the EU's capacity to extract, process and recycle critical raw materials (CRMs) by 2030. The Act mandates that at least 10% of the EU's annual consumption of CRMs should be sourced from domestic extraction, 40% from domestic processing and at least 15% from recycling. Additionally, to mitigate supply chain risks, no more than 65% of the EU's annual consumption of any strategic raw material should come from a single third country. These targets aim to reduce the EU's dependency on external suppliers, add value locally and promote sustainability and circular economy principles.

Supply risk is much more important than the scarcity of natural resources (IEA 2023). In this general context of policy and actions of the EU, the role of this project falls under the first aspect of providing knowledge concerning primary and secondary resources that could be used to prioritise the recovery of mining waste in conjunction with the potential restarting of some of the historical mining operations in the Nordic countries (SGU & Naturvårdsverket 2023).

A primary resource is considered as the original ore deposit before mining has occurred (this is represented by the *in situ* resource, and it can consist of either primary or secondary enrichment ores). By secondary resource, we refer in the report to post-mining and production process products, such as tailings, waste rock, slag, sludge or other secondary materials resulting from industrial processing.

2.1 Macro-economic factors influencing metal prices

Geopolitical events or trends that condition how economies develop over the long term allow the forecasting of commodity consumption (Černý et al. 2021). There is an important connection to make between these large-scale trends and commodity price fluctuations (volatility) over different time intervals. This is because variation in the demand for or supply of commodities in response to their consumption is shaped by policy, the geopolitical landscape and other global-scale events capable of influencing economic stability and its development. Recent examples of the impact of geopolitical and other global macroeconomic trends include the following:

1. The economic tightening imposed by EU states to abate inflationary conditions. Economic tightening in the EU refers to measures such as increasing interest rates or reducing government spending to control inflation. These actions can reduce people's spending power, leading to a lower demand for commodities and potential price decreases (Hancock & Tamma 2024).
2. The Ukrainian war with its impact on energy and food pricing. The Ukrainian conflict has affected commodity markets, particularly for energy and food. Uncertainty and disruptions in supply, primarily from the conflict zones, can lead to increased prices due to fears of scarcity (Tani 2024a).
3. The latest conflict in the Middle East has raised geopolitical risks for commodities, inducing shortages in the supply of energy-related commodities. Conflicts in the Middle East often impact the supply of oil and gas, leading to price volatility. As this region is a key supplier, any geopolitical instability can cause global market fluctuations, affecting energy prices and economic planning (Tani 2024b).
4. The COVID-19 pandemic. The pandemic led to unprecedented changes in the global demand for commodities. Lockdowns and reduced industrial activity caused drops in some commodity prices, while others increased due to supply chain disruptions (Moosavi et al. 2022).
5. Global warming influences the consumption patterns of raw materials. Efforts to reduce greenhouse gas emissions can decrease the demand for fossil fuels and increase the need for renewable energy sources, impacting the raw materials market related to energy production (Fig. 1.1) (Bobba et al. 2020, Carrara et al. 2023).
6. Technological development has always had a major impact on the consumption of raw materials. An interesting new trend is the impact of generative AI (Barbosa et al. 2024). There is likely to be an increased demand for the computational resources necessary to train and run AI models, including a greater need for data centres. These data centres require substantial amounts of raw materials such as rare earth elements (REEs) and copper for construction and operations.
7. The increased tendency of governments involved in or potentially affected by war to produce weapons. Recent events and ongoing conflicts, such as the war in Ukraine, have influenced plans and policies concerning the production of weaponry. Ukraine, for instance, while outgunned by Russia, is planning to ramp up its production of drones, which have proven integral in modern warfare. The European Union is also responding to the heightened threat environment by planning to transition its defence industry to a war footing (Fig. 1.2) (Hancock & Tamma 2024).

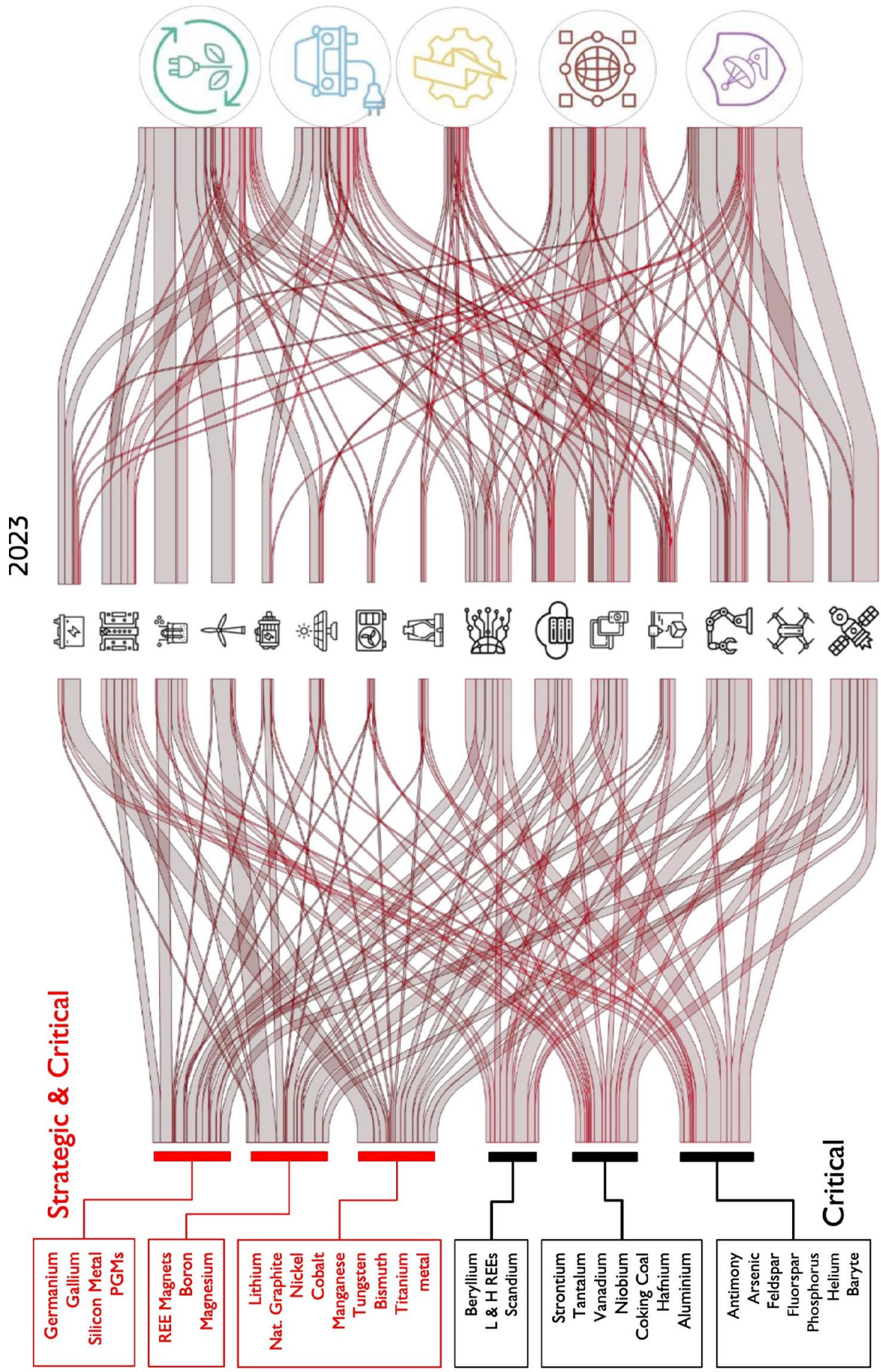


Figure 11. Supply chains of raw materials needed in the green energy transition and special industries (Carrara et al. 2023).

Supply risk for critical raw materials in military applications

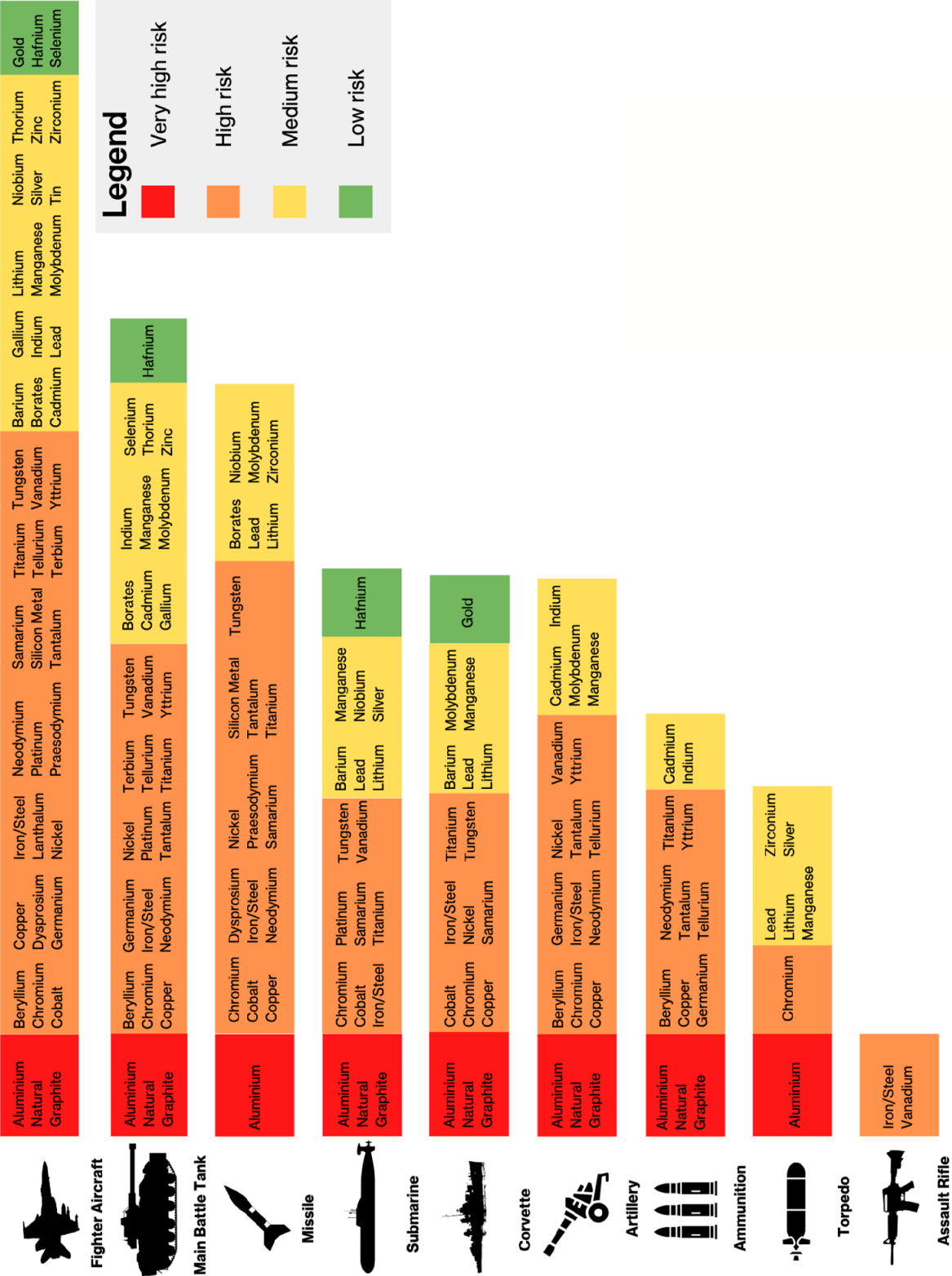


Figure 1.2. Supply chain risk in military applications, adapted from Girardi et al. (2023). The supply risk could be aggravated by the increase in weapons production in response to the recent conflicts in Ukraine and the Middle East, the Israel–Hamas war (Gaza conflict zone) (Jacobin 2024).

2.2 Current outlook

In this section of the report, we examine the role of macroeconomic factors in controlling commodity prices to better understand how policies that invest in the sustainable recovery of CRMs can help in preventing economic shocks related to conflicts or the increased demand for CRMs.

2.2.1 Short-term commodity price stability

The World Bank provides an annual review of commodity prices and yearly and quarterly discusses the commodity market outlooks (World Bank 2023). Understanding the interconnection between commodities and macroeconomic trends can have a large impact on how industries operate in the short- and long-term economic environment to fulfil the needs of future economies. Figure 1.2 illustrates this connection between the usage of CRMs such as aluminium and natural graphite in the production of weapons for defence applications. According to the World Bank (WB), the occurrence of military conflicts can have a significant impact on the commodity prices. The effects would be seen on both sides, as the consumption of CRMs would increase to produce more weapons (Fig. 1.2) and supply chain shocks may occur, dominantly affecting energy prices if barriers or bottlenecks develop.

Before the latest conflict in the Middle East began, voluntary oil supply cuts by OPEC producers pushed up energy prices by 9% in Q3 2023. In general, the prices of commodities have remained elevated, approximately 45% above the 2015–2019 average. Except for natural gas (more than 35% increase in price, Fig. 2.1), the impact of the latest conflict has been muted. Prices of oil and gold have risen moderately, but most other commodities have remained relatively stable. In this context, conflict escalation would represent a major risk. The WB finds this risk relatively low, indicating that the effects of the actual conflict are likely to remain moderate; the baseline forecast is that commodity prices will decline slightly over the next two years.

Looking specifically at metal prices, prolonged disruptions to energy markets (major reductions in oil supply) could raise the production costs of energy-intensive metals such as aluminium and zinc. In its historical analysis of energy shocks, the WB makes important comparisons with past oil supply disruptions in the Middle East, highlighting the importance of recent diversification of supply sources. "Unlike the 1970s, when the global oil market relied heavily on a few producers, especially in the Middle East, oil supplies now come from many sources (IEA 2023)." In addition, much higher gold prices would be expected given the increased geopolitical risk associated with the escalation of a conflict (Bilgin et al. 2018, World Bank 2023).

Short-term commodity prices were already following a downward trend before the Middle East conflict (2% drop in Q3 2023). This was expected in response to weakness in China's heavy industry sector and housing construction, offsetting, for instance, the increase in consumption of resources used in the manufacturing of renewable energy products.

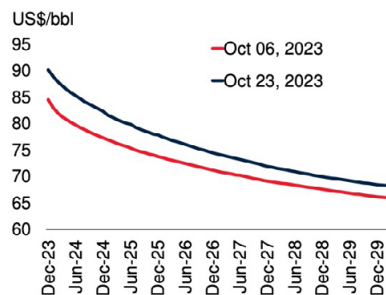
Globally, elevated interest rates have exacerbated the downward trends of some of the commodities used in the construction and manufacturing of goods (e.g., Cu, Zn, Al and coal prices have shown major declines over the

past two years). The prices for minerals used in electric vehicles and battery production, such as cobalt, lithium and molybdenum, have followed the downward trend in base metal prices. However, prices are expected to remain volatile over the short term due to the stratified and concentrated nature of mineral markets. This short-term volatility is affecting the small ventures that invested heavily in the development of projects focused on the recovery of CRMs connected with the green energy transition metals, such as lithium (Fig. 2.2) (IEA 2023). For instance, junior mining companies venturing into lithium production are currently confronting significant financial strain due to the plummeting prices of lithium. With low lithium pricing, these companies are struggling to secure the necessary capital for exploration and development, which threatens their sustainability and growth potential in the highly competitive battery materials market (S&P Global 2024).

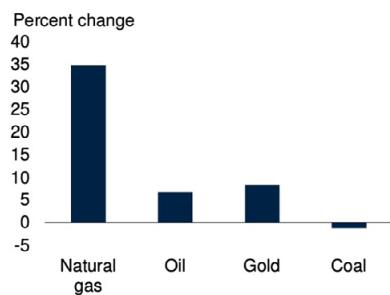
A. Daily prices of Brent crude oil



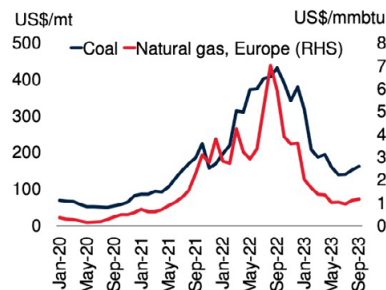
B. Brent future prices before and after the attacks on Israel



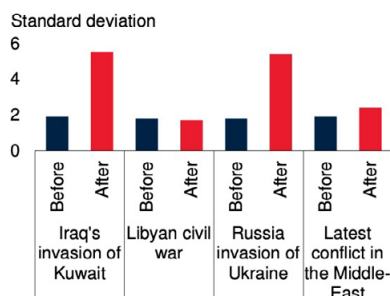
C. Price changes in selected commodities since the onset of the conflict (October 6, 2023)



D. Coal and natural gas prices



E. Oil price volatility before and after conflicts



F. Real oil prices

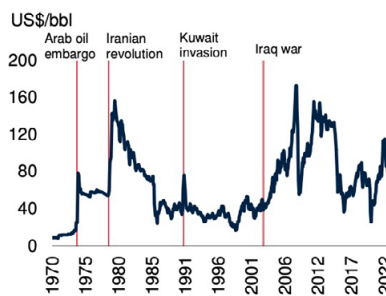
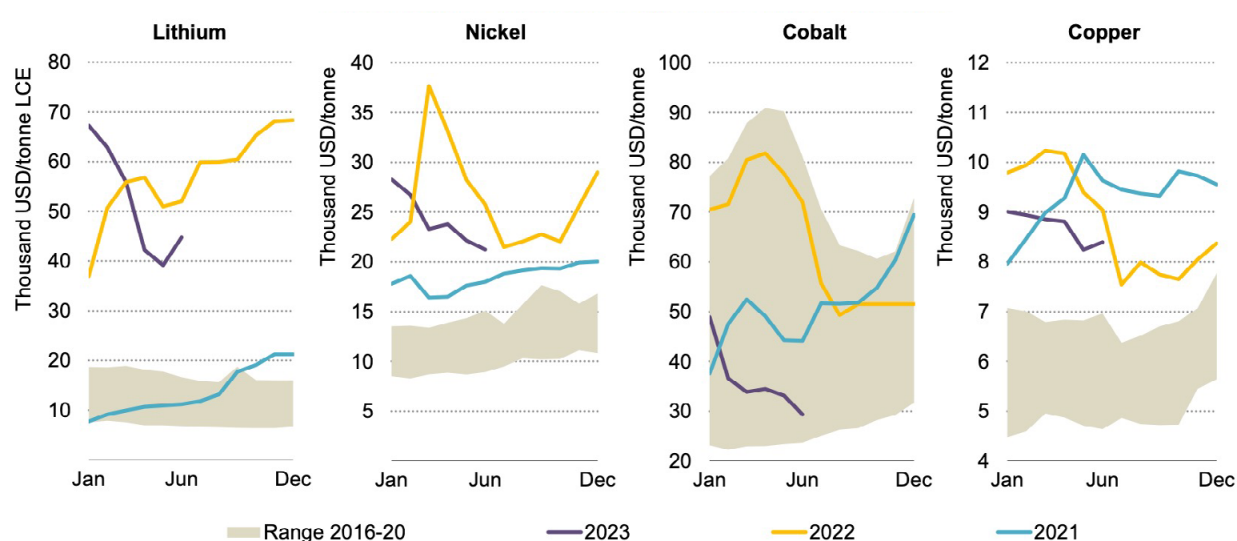


Figure 2.1. Commodity market responses to the onset of the latest conflict have so far been generally modest (A–D), and prices are expected to decline in 2024 under the baseline forecast. Nevertheless, similar geopolitical events since the early 1970s (E–F), often marked by military conflicts, have been associated with higher oil prices and heightened volatility (World Bank 2023).



IEA. CC BY 4.0.

Notes: LCE = lithium carbonate equivalent. Assessment based on LME Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices (nominal).
Source: IEA analysis based on S&P Global.

Figure 2.2. Price development for selected energy transition minerals and metals (IEA 2023).

2.2.2 Long-term commodity price projections

The International Energy Agency (IEA) helps in formulating responses to energy price shocks. In its Critical Minerals Market Review (IEA 2023), the IEA reaffirms records in the deployment of energy transition minerals, which are becoming a major focus for the mining and metal markets. The demand for CRMs is set to rapidly increase in all the IEA scenarios. The IEA considers three distinct predictive modelling scenarios with variable goals and policy levels:

- (1) The Stated Policies Scenario (STEPS): This scenario maps out a consumption trajectory that reflects current policy settings, based on a detailed assessment of what policies are in place or are under development by governments around the world;
- (2) The Announced Pledges Scenario (APS): This scenario assumes that all long-term emissions and energy access targets, including net zero commitments, will be met on time and in full, even where policies are not yet in place to deliver them;
- (3) The Net Zero Emissions by 2050 Scenario (NZE): This scenario sets out a pathway for the global energy sector to achieve net zero CO₂ emissions by 2050. Global needs for all scenarios are expressed as million tonnes (Mt) of annual material consumption by 2030 and 2050 (Fig. 2.3).

For instance, in the APS scenario, demand more than doubles by 2030. In the NZE model, demand for CRMs grows 3.5 times by 2030, reaching 30 Mt. EVs and battery storage are expected to be the main drivers of these increases (Fig. 2.3). Industries across the globe are responding to this CRM demand with a pipeline of projects that are starting to provide new supply channels that will likely meet the requirements for the energy transition. However, IEA

argues that there will be challenges ahead, for instance in meeting the requirement of NZE (this scenario puts more emphasis on emissions reduction), which might require more CRM producers, especially if the purity of the products is considered (battery-grade products require higher purity than technology-grade products). Further to this, it is expected that some of the CRM producers will experience delays and might encounter significant overspending given the observed short-term volatility of commodity prices. However, over the medium to long term, the expectation is that mineral prices will remain high (above the 2016–20 average, Fig. 2.2), especially if supply-side constraints occur in concert with geopolitical disruptions or speculative financial activities influencing commodity stocks on the exchanges (e.g., the London Metal Exchange, LME).

2.2.3 Considerations of the impact of short-term price instabilities and long-term pricing models on CRM exploration and mining

Given that conflicts are having a moderate impact on the short-term volatility of commodity prices, it is expected that mineral prices will remain at elevated levels and the relative demand for CRMs will be prevalent over the medium to long term, with short-term volatility influenced by shocks caused by supply-chain disruptions either connected with recessionary economies or other geopolitical conditions (e.g., significant escalation of conflicts).

The major impacts observed to date can be seen in how governments are rapidly creating a host of policies to incentivise the growth of the new economies (Biden 2022a,b,c, EU Commission 2023a), followed by a rich pipeline of projects focused on the mining and recovery of CRMs.

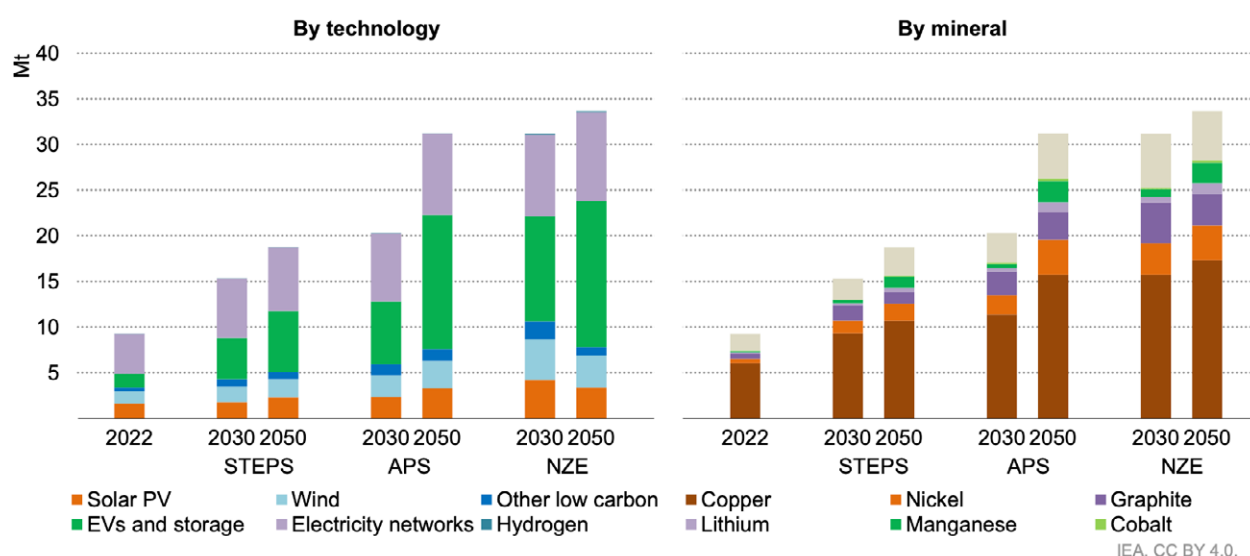
Interesting opportunities in advanced projects on CRMs are focused on lithium, graphite, vanadium and REEs + phosphorus in the Nordics. For instance, the Bergby project in Sweden, operated by United Lithium Corp., is focused on lithium mineralisation in LCT-pegmatite, with significant lithium oxide grades identified. Similarly, the Keliber project in Finland, managed by Keliber Oy, a subsidiary of Sibanye-Stillwater, aims to produce battery-grade lithium hydroxide from substantial lithium deposits, with production expected to commence soon.

On the graphite front, the Woxna project, also in Sweden and operated by Leading Edge Materials Corp., includes the Woxna graphite mine (currently under care and maintenance). This mine is considering restarting the production of high-quality natural flake graphite, targeting the battery and high-tech industries. Talga Group's Vittangi graphite project in northern Sweden aims to produce up to 120,000 tonnes of graphite per year. In northern Sweden, the Airijoki project, owned by Kendrick Resources PLC, is focused on vanadium exploration, with substantial vanadium resources contained within magnetitiferous rock. Vanadium essential for steel alloys and redox flow batteries used in energy storage. Airijoki has an inferred mineral resource comprising 44.3 Mt at 0.4% V_2O_5 . Airijoki and Koitelainen (Finland) hold the potential to produce vanadium magnetite concentrates with a grade in the top 2–3 of projects globally.

For REEs and phosphate, several significant projects are underway. The Sokli project in Finland, operated by Finnish Minerals Group, is focused on both phosphate and REEs, hosting large phosphate rock deposits and substantial

quantities of REEs vital for high-tech applications. In southern-central Sweden, the Norra Kärr project, managed by Leading Edge Materials Corp., is a major heavy rare earth element (HREE) site outside China, with critical elements such as dysprosium and terbium essential for electric vehicle and wind turbine magnets. In Norway REEs are targeted in the Fen carbonatite complex by two companies; Rare Earths Norway and REE Minerals AS. Fen is continental Europe's largest documented REEs deposit. Lastly, the Greenland REE project, under Greenland Minerals A/S, a subsidiary of Energy Transition Minerals Ltd., includes the Kvanefjeld project, one of the world's largest undeveloped REE deposits. It contains significant amounts of neodymium, praseodymium, dysprosium and terbium, crucial for renewable energy technologies and advanced electronics.

If we consider active projects with abundant secondary resources, the Nordic region is host to a significant volume of tailings from the mineral industry, presenting a considerable opportunity for the extraction of CRMs. Notably, the REE tailings from Kiruna, Sweden, constitute a massive waste stream with untapped potential for CRMs and other valuable elements (Mining Technology 2020, Reuters 2020, Högnelid 2021, PorterGEO 2023). Similarly, in Grängesberg, Sweden, iron flotation processes have resulted in tailings rich in apatite, phosphate and REEs (Anglesey Mining 2022). Alum shale, historically used for producing dyes, pigments and metals, is known for its content in critical elements representing another possible source of useful raw materials. A host of new technological developments is occurring. For instance, the Boliden company's Jarogain process is an innovative approach aiming to recover valuable materials such as indium, germanium, gallium and precious metals from jarosite, a zinc residue waste (Salminen 2024). Lastly, the Siilinjärvi plant in Finland sees potential in the extraction of REEs from phosphogypsum waste, which could be significant enough to support the construction of battery electric vehicles (BEVs). Together, these various projects and resources highlight the potential of the Nordics as a crucial hub for CRM recovery and sustainable resource management (Bergfald et al. 2024).



Notes: STEPS = Stated Policies Scenarios; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Includes most of the minerals used in various clean energy technologies, but does not include steel and aluminium.

Figure 2.3. Mineral requirements for clean energy technologies by scenario (IEA 2023). The critical minerals demand for clean energy technology is set to grow by up to 3.5 times by 2030.

These examples represent important active initiatives for the exploitation of the CRM potential. However, at present, there is no systematic inventory (except for Sweden) listing the CRM potential of mining waste across the Nordics. The following sections present a discussion of the project objectives and a review of the production history of the Nordic countries. This is to inform the reader of the diversity of mineral exploitation across the Nordics and help with the delineation of a workflow that supports the development of this inventory dedicated to mining waste.

2.3 The Nordic Sustainable Minerals Programme

The Nordic countries need to produce and process more minerals to meet expected increases in the global demand for natural resources connected with some of the macroeconomic factors discussed in the previous sections of this report, such as the energy transition and relative investment in renewables. Between 2021 and 2024, the Nordic Trade and Industry Ministers launched eight initiatives to bolster a green economic resurgence post-COVID-19. These initiatives, managed by Nordic Innovation under the Nordic Council of Ministers, aim to transform the Nordics into the most sustainable and integrated region by 2030. A key project among these is the Nordic Sustainable Minerals Programme (NSMP), designed to establish the Nordic nations as leaders in sustainable mineral production.

A 2021 report by Nordic geological surveys, energy authorities and Reykjavik University (Eilu et al. 2021) underscores the untapped potential in the Nordic region for CRMs essential for a sustainable future. The report indicates a steady rise in CRM consumption, noting that recycling alone cannot meet this growing demand. Furthermore, raw material substitutes, where available, often lead to inferior performance and resource wastage, confirming the future need for primary mineral resources.

2.4 Work package 2: Recovery & Recycling

The Work Package 2 (WP2) project stemmed from this initiative (NSMP) and provided independent research and data compilations from various geoscientific sources (Gaâl et al. 2012, Cassard et al. 2014, Huisman et al. 2016, Bide 2020, Sadeghi et al. 2021, Jonsson et al. 2023, Hollis et al. 2024), aiming to create a prototype Nordic Database (ND) for mineral deposits and their associated waste streams and to document a series of case studies of historical and presently active sites (industrial smelters and waste processing facilities) with significant mining waste in the Nordics. Current European databases are fragmented or lack detailed information on secondary resources (Eilu et al. 2021). A comprehensive ND would aid in research, exploration, policymaking and planning, representing a resource that acts as an inventory of primary ores and secondary resources. Much of the technology used for the distribution of these data has been utilised for decades for primary resources, relying on physical server architectures. The question posed in the planning phase of this project was any alternative exists for presenting mineral resource

information that would render it more accessible, increasing its usage and supporting the digital and green energy transition trends, for instance, by enabling the utilisation of more advanced services connected to the AI revolution.

Part of the research targeted this overarching objective of creating a more sharable resource, supporting data interactivity and more advanced classification systems for natural resources (for instance, enabling rapid and simplified use of SQL language to interrogate the mineral resources data, a significant advancement in terms of information search and understanding). Some of the general objectives of WP2 had as a priority an increase in circularity and extraction from secondary metal and mineral resources (metal/mineral recovery) while contributing to digitalisation and public access to data. The use of advanced GIS representations that leverage up-to-date cloud environments to conduct analytics on primary and secondary CRMs was also considered a general goal of the project to demonstrate possible solutions for defining the CRM potential.

To achieve these goals, several steps were considered, which involved:

- (1) The development of geochemical, mineralogical, geophysical, environmental and community relation studies on secondary resources of historical mine waste and active industrial operations located in some of the Nordic countries (section 3);
- (2) The development and design of a database and new data capturing strategies with the objective of facilitating the identification of key mining waste sites with significant CRM potential (section 4). Secondary resources are difficult to evaluate (Nassar et al. 2015, McNulty & Jowitt 2021), and research was thus targeted at migrating existing classification methodologies used in comparing primary resources to mining waste. To fulfil this objective, preliminary research was conducted to understand why it is important to reutilise waste and to evaluate several existing best practices that illustrate the benefits of recovering CRMs or other valuable by-products from waste material.

2.5 Definition and significance of secondary resources in the context of recovery of co- and by-products

Mining waste represents a by-product of mining (i.e., overburden, waste rock, tailings and slag) that is historically linked to environmental harm and resource loss (Fig. 2.4). Over the years, the focus has, however, shifted towards more sustainable waste management aiming at recovering co-products and by-products from such waste in the mineral value chain.

The mineral value chain in the context of, for instance, battery and magnet production downstream refers to the entire series of processes involved in transforming raw minerals into finished batteries and magnets. It is important for the EU to strengthen the resilience of all value chain stages (upstream, midstream, downstream) to be entirely self-sufficient when it comes to lithium battery and neodymium magnet technologies.

This change of focus offers several advantages, starting with: (1) the better use of natural resources centred on reducing the need for further extraction and promoting the full utilisation of extracted material in line with a circular economy vision (Kinnunen & Kaksonen 2019); (2) mitigating the environmental impact by lowering waste volumes and potential pollution, and by decreasing greenhouse gas emissions due to the more energy-efficient recovery processes; and, finally, by (3) boosting the economic prospects of mining companies through additional revenue from the valuable materials reclaimed from the waste (Pokka et al. 2024).

This approach supports environmental sustainability goals and promotes a more economically viable mining industry by turning waste into wealth. Examples of co- and by-products recovered from mining waste globally include platinum group metals (PGMs) from nickel and copper mining (SRK Consulting 2020), rare earth elements (REEs) from coal by-products (Hart & Levins 1988, Pan et al. 2021, Echeverry-Vargas & Ocampo-Carmona 2022, Delitsyn et al. 2023) and studies on special metals such as indium, germanium and gallium that occur in complex sulphide ores (Frenzel et al. 2019, Paschalis 2023) and REEs (Högnelid 2021) in iron ore deposits. Various industries (i.e., electronics, automotive sectors) rely on the availability of these materials (Fig. 1.1). The exploitation of mining waste in this context serves the dual purpose of tackling the growing need for critical raw materials, while simultaneously promoting the more sustainable and environmentally responsible use of resources.

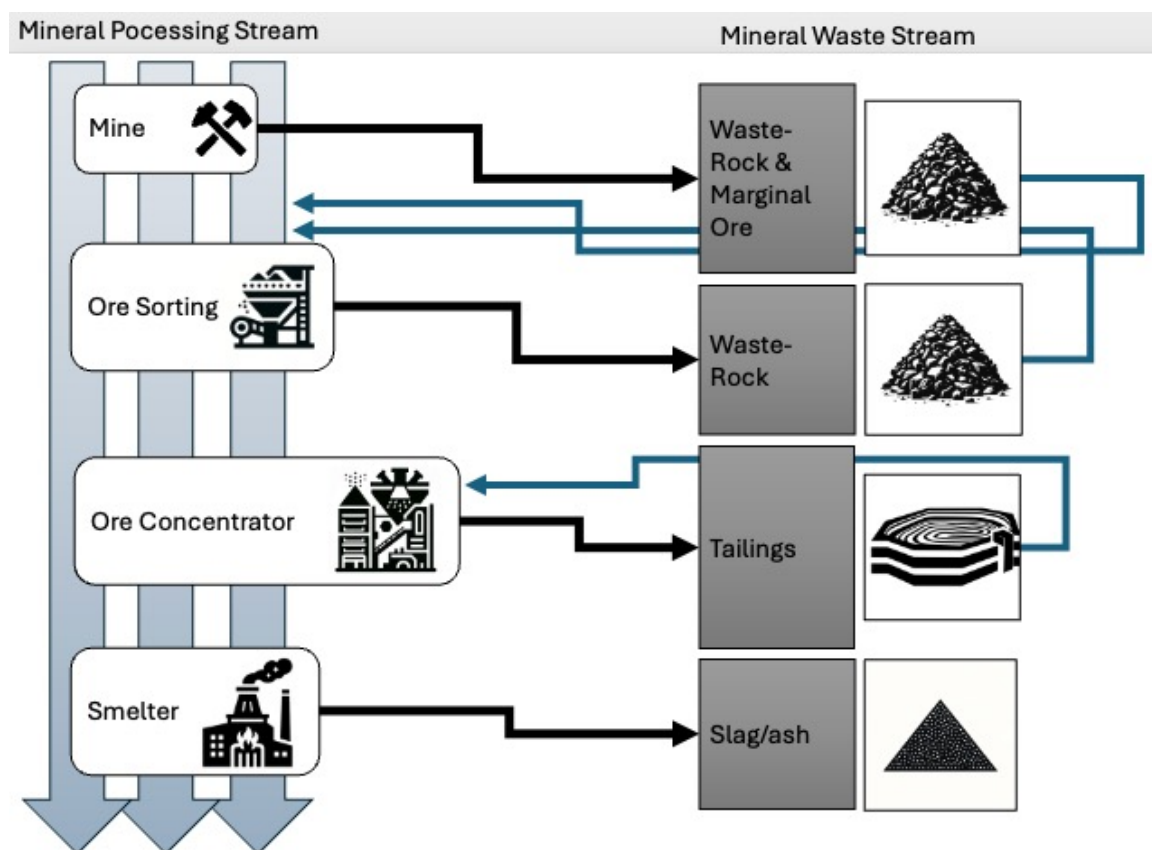


Figure 2.4. Mineral extraction phases and the relative mineral waste produced along the value chain. Blue arrows illustrate how the waste material feeds back into the mineral extraction processes, such as material sorting and concentration (modified) (Hallberg & Reginiussen 2019).

Exploitation of mine waste for the recovery of co- and by-products is a growing area of interest (Adrianto et al. 2023), with efforts generally focusing on the development of innovative techniques, leading, for example, to an improved capability to recover valuable metals from already processed material, where previous extraction was not economically viable. For instance, the recovery of rare earth elements (REEs) as coal by-products is an interesting practise that is becoming increasingly popular in response to the growing demand for REEs in emerging technologies (Pan et al. 2021).

The implementation of hydrometallurgical techniques (section 3.5), involving the extraction of metals from ore or mining waste by selective leaching, as an alternative to pyrometallurgy represents an additional example of these practices (Borra et al. 2016, Pan et al. 2021, Adrianto et al. 2023). Hydrometallurgy can, for instance, be applied to recover platinum group metals (PGMs) from nickel or copper waste.

2.6 Importance of CRMs in the green energy transition

In recent years, a set of strategic programmes and regulations has been adopted at the European level having the clear objectives of promoting the green and digital transitions while strengthening the EU's position in terms of CRM availability. The initiatives promoted in this context include the European Green Deal (EU Commission 2019), the REPowerEU Communication (EU Commission 2022a), the Joint Communication on Defence Investment Gaps Analysis and Way Forward (EU Commission 2022b) and the Digital Strategy (EU Commission 2023b). In addition, the EU Critical Raw Material Act, aiming at ensuring access to critical resources and reducing EU dependencies on third countries, entered into force in May 2024.

Research initiatives dealing with CRMs have increased in response to these strategic and political activities both at the European (Guzik et al. 2021) and international level (Bauer et al. 2023) and include, for instance, attempts to estimate the CRM budget of secondary resources in tailing facilities, at mining sites and processing plants (Hallberg & Reginiussen 2019, Tunsu et al. 2019). In this sense, it is important to consider not only unprocessed mining waste often found close to mining operations but also material produced and discarded during the processing (i.e., concentration, smelting) of ores (Kuusela 2015, Werner et al. 2015, Feltrin & Bertelli 2023), which may therefore be located close to processing facilities (e.g., coal power plants, steel mills and ore concentration facilities).

The remainder of this section provides background information on CRMs, specifically on their definition and on the criticality assessment process employed by the EU, which results in a list of CRMs. This list is updated every three years by the European Commission (Bobba et al. 2020, EU Commission 2020b, 2023a), with the most recent update in 2023 defining a total of 34 critical and 17 strategic raw materials (Table 2.1).

Table 2.1. The 2023 list of CRMs, adapted from the EU 2023 report (EU Commission 2023a,c). Strategic minerals (SRMs) and metals are indicated in **italics**. A comparison with the EU 2020 list shows that indium and natural rubber are no longer considered as CRMs. However, important elements such as Cu and Ni are now considered as CRMs.

2023 Critical Raw Materials (Strategic Raw Materials in italics)			
aluminium/bauxite	coking coal	<i>lithium</i>	phosphorus
antimony	feldspar	LREE	scandium
arsenic	fluorspar	<i>magnesium</i>	<i>silicon metal</i>
baryte	<i>gallium</i>	<i>manganese</i>	strontium
beryllium	<i>germanium</i>	<i>natural graphite</i>	tantalum
<i>bismuth</i>	hafnium	niobium	<i>titanium metal</i>
boron/borate	helium	PGM	<i>tungsten</i>
cobalt	<i>HREE</i>	phosphate rock	vanadium
		<i>copper*</i>	<i>nickel*</i>

*copper and nickel do not meet the CRM thresholds, but are included as SRMs.

2023 CRMs vs. 2020 CRMs			
aluminium/bauxite	gallium	phosphate rock	vanadium
antimony	germanium	phosphorus	arsenic
baryte	hafnium	PGM	feldspar
beryllium	HREE	scandium	helium
bismuth	lithium	silicon metal	manganese
borate	LREE	strontium	copper
cobalt	magnesium	tantalum	nickel
coking coal	natural graphite	titanium metal	<i>indium</i>
fluorspar	niobium	tungsten	<i>natural rubber</i>

Legend: CRMs in 2023 and 2020

Black: CRMs in 2023, non-CRMs in 2020 **Red:** CRMs in 2023, non-CRM in 2020

Strike: Non-CRM in 2023 that were critical in 2020

The criticality of a specific material is dependent on two main parameters: its economic importance (EI) combined with the risk associated with its supply (SR). The EI factor provides a measure of the economic importance of a certain material for the EU economy based on end-use applications and the value added of corresponding EU manufacturing sectors, also including a correction index accounting for the substitution of the material. The SR parameter is instead an estimate of the risk associated with potential supply disruption in the EU of a material and it considers factors such as the concentration of primary supply from producing countries (Fig. 2.5 provides a complete illustration of global production of critical and strategic raw materials in 2023), the EU reliance on imports and correction indices associated with recycling and substitution. Figure 2.6 displays the results of the 2023 criticality assessment based on the two above-mentioned parameters; raw materials are considered critical when $SR > 1$ and $EI > 2.8$. Examination of the figure allows some important considerations. Firstly, it is apparent that the group of REEs has some of the highest criticality. The reason for the scoring lies in the strategic importance of this group of elements as a fundamental component in the magnets of electric motors (Hofmann et al. 2018, Bauer et al. 2023) employed in emerging technologies (i.e., wind turbines), combined with a high supply risk due to their production being dominantly in China and therefore dependent on

Global production of critical and strategic raw materials (CRM/SRM)

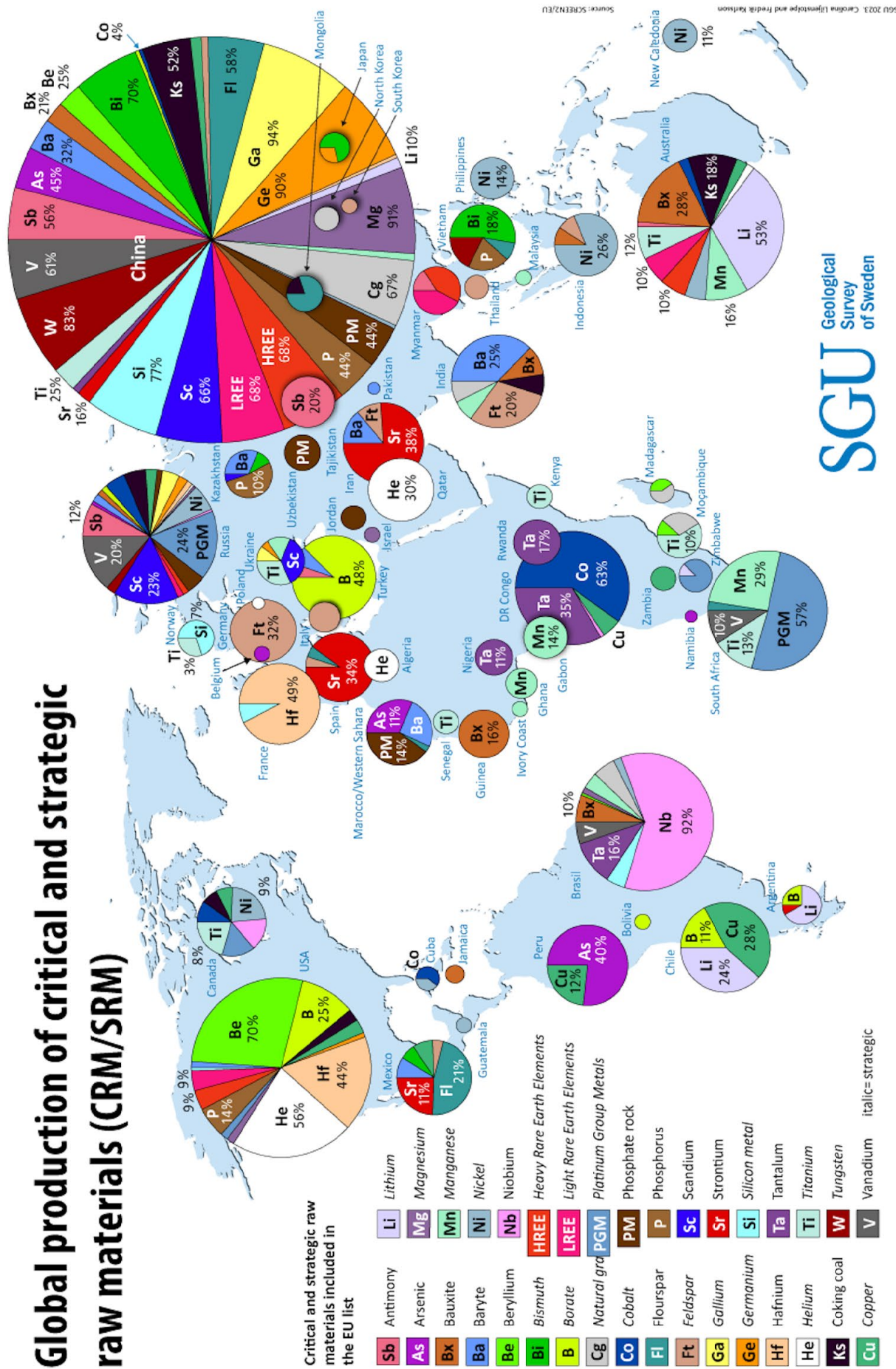


Figure 2.5. The EU relies on imports for 75 to 100% of most critical raw materials (CRMs). Additionally, the production and processing of many CRMs is geographically concentrated, making their geopolitical access vulnerable. Certain CRMs and their associated value chains are predominantly monopolised by specific regions of the world, often by a single country. Source SGU: <https://www.sgu.se/en/mineral-resources/critical-raw-materials/>.

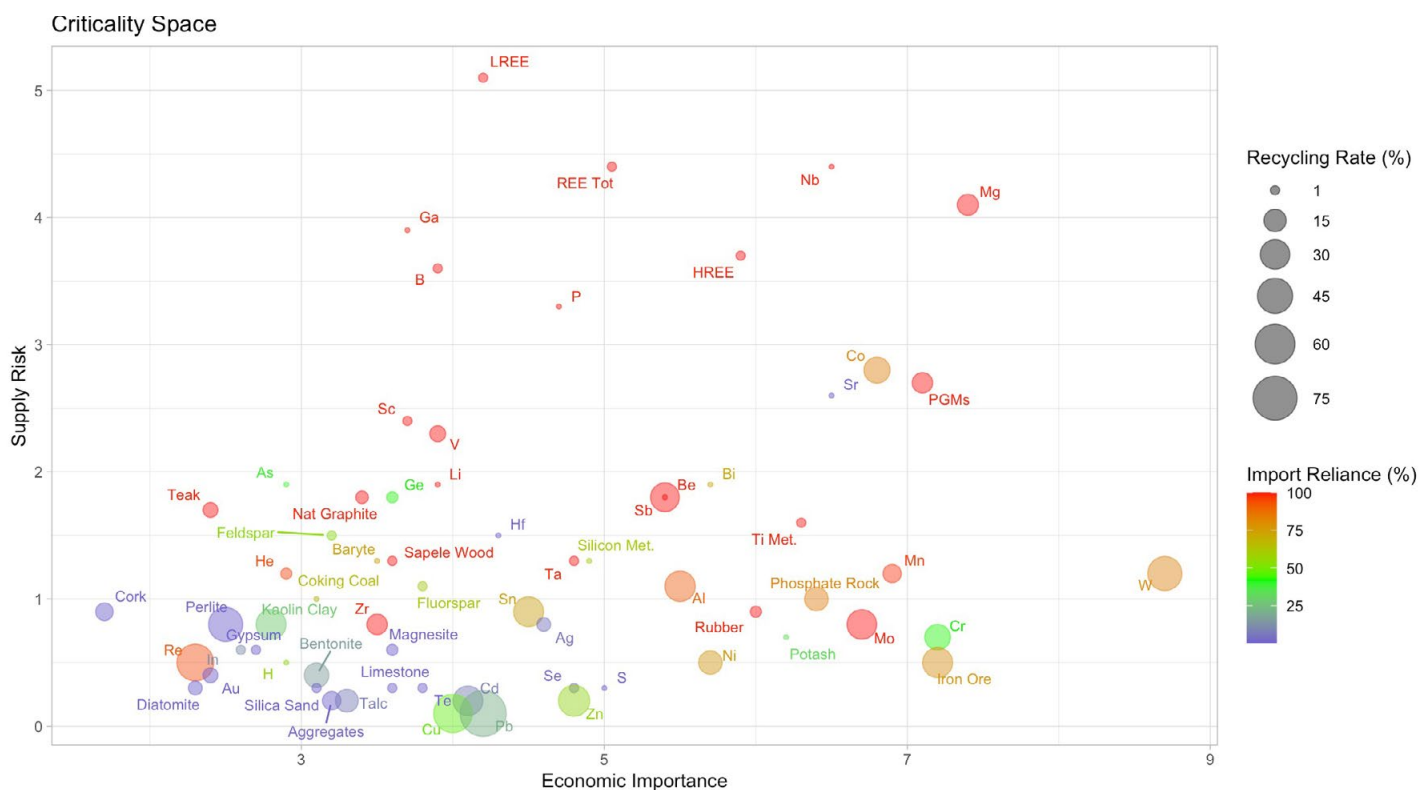


Figure 2.6. Economic importance and supply risk results of 2023 criticality assessment. The size and colouring respectively represent the recycling rate and import reliance of EU countries for each commodity considered in the 2023 assessment.

Chinese export regulations (IEA 2023, Safety and Regulation Bureau of China 2023). Other materials scoring highly in the criticality assessment include platinoids (PGMs), magnesium, cobalt and germanium, which are all essential to current transitions. CRMs thus are often produced and used in small quantities but possess unique characteristics that make them essential ingredients for products in strategic areas such as renewable energy, digital, aerospace and defence technologies (Bobba et al. 2020, EU Commission 2023a,b) (see Fig. 1.1). Copper and nickel do not meet the CRM threshold; however, they were included in the EU 2023 categorisation as CRMs due to their strategic importance in battery production.

The following section provides background on the concept of companionality, used in this contribution as a basis for the definition of CRM potential (Table 4.4). We also focus attention on the mineral/metal production of the Nordics and associated co- and by-products. These terminologies are defined in section 4.1.1.5, together with a discussion of their application to qualify the CRM potential.

2.7 Metal's companionship

The quantities of minerals and metals present in the Earth's crust vary greatly, with most elements occurring at concentrations lower than 5 grams per tonne (Rudnick & Gao 2003). The concentration of an element in ore bodies is a crucial factor determining the economic viability of projects for its extraction (Haldar 2018). In many instances, materials that are considered critical occur in low quantity in association with more abundant elements. These associations depend on the geochemical affinity between elements, as well as on other factors, including element availability and deposit formation conditions. In this sense, these associations can be defined as companionship, in which an element typically occurs with, and its production is tied to, one or two more abundant metals. A classic example of companionship is represented by cobalt and nickel; cobalt is mostly mined as a by-product of nickel, and increasing its production therefore necessarily has repercussions on nickel extraction and prices (McNulty & Jowitt 2021). Figure 2.7 illustrates the "wheel of metal companionship" and Table 2.2 provides an expanded view of companion metals and defines the CRMs associated with each main production metal for the Nordics. This interconnectedness can lead to challenges, as boosting the production of one metal might lead to overproduction and decreased prices for another, affecting profitability and interest in mining.

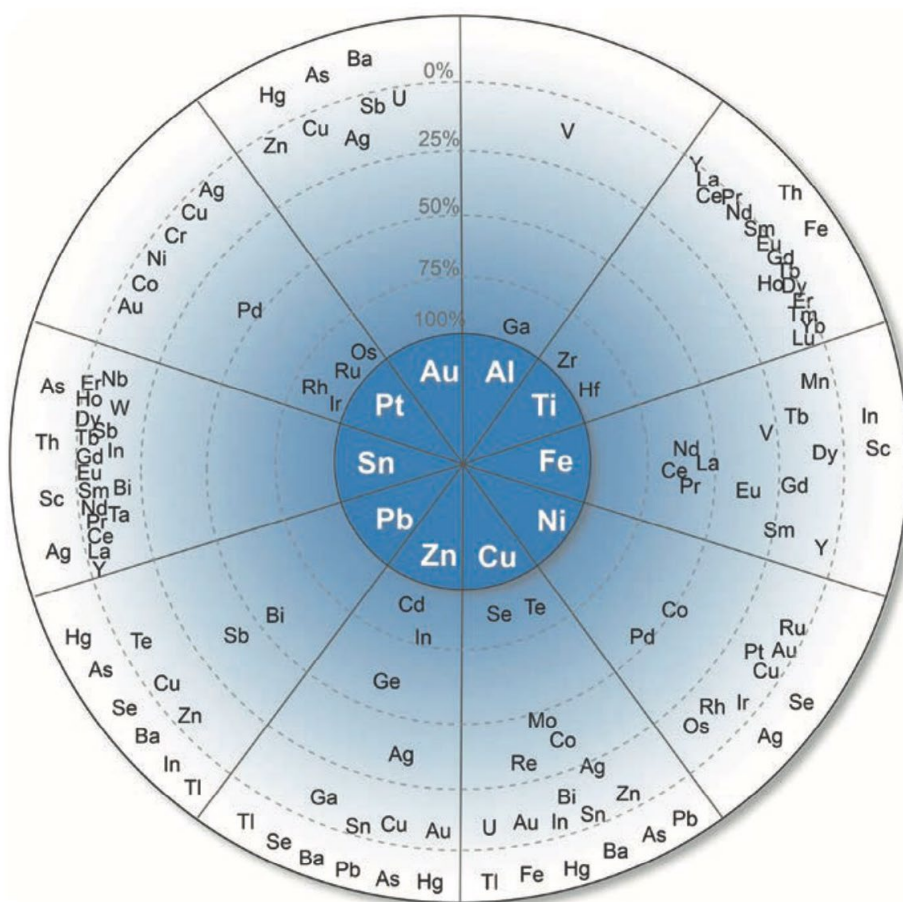


Figure 2.7. The circle of metal companionship. Central to the diagram are the primary metals, while the outer regions portray their companion metals (Nassar et al. 2015). Companion metals in the white area of the diagram are rarely produced with the listed main metals. The closer by-products are to the respective main metals, the higher is the degree of co-production.

Table 2.2. An expanded list of primary production metals and minerals. Companions are listed based on companionality rules (Nassar et al. 2015) and their CRM classification according to the EU Raw Materials Act (EU Commission 2023a).

Mineral and metals (primary production)	Companion*	CRM (2023)
Aluminum (Al)	Ga, V	Al, Ga, V
Titanium (Ti)	Zr, Hf, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Ho, Dy, Er, Tm, Yb, Lu, Th, Fe, (Sc)	Ti, LREE, HREE, Hf, Zr, (Sc), (W)
Iron (Fe)	Ce, Nd, Pr, La, Eu, V, Sm, Gd, Tb, Y, Dy, Mn, (Sc), In, Mo	LREE, HREE, (Sc), Mn, V, In**
Nickel (Ni)	Pd, Co, Os, Rh, Ir, Pt, Cu, Au, Ru, Ag, Se, (Sc), Mo	Ni, PGM, Co, Cu, (Sc)
Copper (Cu)	Se, Te, Mo, Re, Co, Ag, Bi, U, Au, In, Sn, Zn, Tl, Fe, Hg, Ba, As, Pb	Cu, Co, Bi, In**, Ba, As
Zinc (Zn)	Cd, In, Ge, Ag, Ga, Sn, Cu, Au, Tl, Se, Ba, Pb, As, Hg	In, Ge, Ga, Cu, Ba, As
Lead (Pb)	Bi, Sb, Te, Cu, Zn, Hg, As, Se, Ba, In, Tl	Bi, Sb, Cu, As, Ba, In**
Tin (Sn)	Nb, W, In, Bi, Ta, Er, Ho, Dy, Tb, Gd, Eu, Sm, Nd, Pr, Ce, La, Y, As, Th, Sc, Ag	Nb, Ta, W, In, Bi, LREE, HREE, Sc, As
Platinum (Pt)	Ir, Rh, Ru, Os, Pd, Au, Co, Ni, Cr, Cu, Ag	PGM, Co, Ni, Cu
Gold (Au)	Ag, Zn, Cu, Sb, U, Hg, As, Ba	Cu, Sb, As, Ba
Uranium (U)	HREE, LREE, Pb, Bi, Zr, Hf, V, Mo, Cu, Ni, Se, As, P	HREE, LREE, Bi, Hf, V, Cu, Ni, As, P
Graphite (C)	HREE, LREE, Be, Li, V, Fe, S	Natural Graphite, HREE, LREE, Be, Li, V
Lithium (Li)	K, B, Cs, Rb, Ta, Nb, Na, Mg, Ca, S, (HREE), (LREE)	Li, B, Ta, Nb, Mg, (HREE), (LREE)
Phosphorus (P)	Ca, HREE, LREE, F, S, U, Th	P, HREE, LREE, F
Silicon (Si)	Fe, (HREE), (LREE), Li, Be, Feldspar	Si, (HREE), (LREE), Li, Be, Feldspar
Manganese (Mn)	Al, HREE, LREE, Si, Fe, Co, Ni, Cu, S, Ca	Mn, Al, HREE, LREE, Si, Co, Ni, Cu

* Nassar et al. (2015)

** indium is considered a critical element for the Nordic countries.

() rare occurrence/association

The companionality concept is also relevant to secondary resources in the context of attempting to qualify and quantify the likely CRM budget of mining waste. This is particularly important in regions such as the Nordic countries, with abandoned mines and unexplored ore sites, where the concept can be applied to specific types of waste with well characterized primary resources. An example of such application is reported in section 4.1.

2.8 CRMs and non-CRMs considered important for trade in the Nordic countries

The potential for CRMs in the Nordic countries is quite large, although it varies greatly. For instance, Norway is known for its titanium, graphite and silicon mines, while Sweden has the most important iron oxide apatite (IOA or Kiruna-type) ore mines and volcanogenic massive sulphide (VMS) deposits, although the latter are also an important resource in Finland and Norway. Finland has unique orogenic Au and Ni–Cu–PGE deposits and more complex polygenetic ores. This variation in mineral resources, associated with the complex tectonic and metamorphic history, occurs both within each country and among the different countries, as well as in the level of knowledge about the specific metals and minerals. Current understanding of CRM resources and their locations in these countries is summarised in several publications (Eilu et al. 2021, Jonsson et al. 2023, SGU & Naturvårdsverket 2023, Bergfald et al. 2024, Camitz et al. 2024, Casey et al. 2024). The reason why the Nordic region has such potential is because its bedrock shares a similar geological and metallogenic history with other mineral-rich countries around the world. Large areas are also characterised by sparse vegetation, mostly free of ice, and comparable in size to the most mineral-rich regions of Canada, the USA, Australia, South Africa or Brazil (Eilu et al. 2021).

For most CRMs important to the EU, the Nordic countries show a moderate to major potential for resources. Table 2.3 highlights how some Nordic CRM resources are significant not only in Europe but globally in their applications to technology, construction and renewable energy sources.

Some of the Nordic countries share a strong tradition in the mining of metal-liferous deposits that are represented by both CRMs and non-CRMs. Among the non-CRMs, it is worth mentioning chromium, molybdenum, gold, silver, iron, zinc and lead. Below, a discussion of mineral and metal production provides additional information on the main deposits and processing facilities that contributed to the mineral trade of these non-CRMs, essential to economic development in the Nordic countries.



View of the Løkken area. Photo: NGU.

Gold contributes to economies differently when compared to other metals, and its mining may lead to significant pollution of the environment. This precious metal is dominantly used in the production of jewellery (50–60%) and in the financial sector as a storing value asset and for investment purposes (35–40%). Only 7–10% of its usage is attributed to technology and other industrial applications (World Gold Council 2024). This diverse range of applications indicates that this commodity was instrumental to economic trade and financial stability, although at the same time being non-critical for the green energy transition means there should be concern about the amount of Au mining conducted in the Nordics. Thus, Au should be mined responsibly. It is likely that the role of this metal will evolve and progressively become prominent for energy-related applications. For instance, gold is already used with chromium, iron, silver, lead, molybdenum and zinc in constructing wind turbines and solar panels, the cornerstones of clean energy systems. Elements such as cadmium, chromium, silver and tellurium also play a significant role in energy storage solutions, such as batteries, although they are not currently considered critical or strategic.

Among the non-CRMs recently reclassified as strategic CRMs (EU Commission 2023a), copper, manganese and nickel are crucial for creating carbon-neutral energy infrastructures. Copper is heavily used in electrical wiring, heat exchangers, electric motors in renewable energy applications and in the construction of solar panels. Manganese, nickel and titanium fortify steel and other alloys for infrastructure and are prevalent in battery technology for energy storage. They are typically alloyed directly with iron, in contrast to copper's typical use in its refined state.

The demand for copper and nickel is rising, especially for energy-related applications, and may soon challenge their traditional industrial roles. Iron contributes to the manufacturing of steel for wind turbine structures and forms the magnetic core of electric motors, essential for generating clean energy. Chromium enhances the durability and corrosion resistance of stainless steel used in various renewable energy structures. Zinc, in the form of zinc–air batteries, offers sustainable energy storage solutions and protects other metals from corrosion through galvanisation, lengthening the life cycle of green energy infrastructure. Even lead, which is subject to environmental restrictions, is used in lead–acid batteries for solar power storage solutions. These materials, including the applications of molybdenum, chromium, zinc, lead and iron, are integral in transitioning towards renewable energy sources, highlighting their importance in green technologies.

*Table 2.3. The most relevant CRMs in the Nordic countries based on potential future production delineated by their inferred resources and subdivided into critical and strategic (listed in **bold italics**), <https://www.gtk.fi/en/critical-metals-and-minerals-in-fennoscandia/>.*

CRMs and utilisation in Nordic countries		Global share of Nordic countries (%)		Mineral/metal potential of the Nordics (metric tonnes)
CRM/ Commodity	Main application(s)	Extraction share	Processing share	Known resources
Cobalt*	Essential for many electrode types in Li-ion batteries.	1.3	14.7	489,700
Copper	Electrical wiring, plumbing, industrial machinery, essential component in renewable energy systems.	0.7	1.6	18,540,000
Feldspar	Solar panel production, improves both light transmission and durability extending the lifespan of the panels. Glass and ceramic applications	<2	-	Potentially Large
Hafnium	Solar cells, infra-red and fibre optics.	0	0	1,100.000
Lithium	Li-ion batteries. Vehicles and energy storage applications.	0	0	78,240
Manganese	Steel production and alloys, essential in battery production and electronics.	0	<1	10,688,000
Natural Graphite	Essential for many electrode types in Li-ion batteries.	0.9	0.9	30,654,000
Nickel	Stainless steel and alloys, battery production, plating and coinage.	1.5	6.3	7,640,000
Niobium	Superalloys in power generators, turbines, super-conducting magnets.	0	0	6,612,000
Phosphate Rock/ Phosphorus	Fertilizers and animal feed, important for agriculture and food production.	0.5	-	>260,000,000 to several billions
Platinum group metals (PGM)	Essential in fuel cell and hydrogen power technology, extensive electronics applications.	<1	Palladium (0.4), Platinum (0.7)	1,150
Rare Earth Elements	Magnets for electric motors and generators in vehicles and wind turbines, fuel cells and batteries.	0	Praseodymium (0.1), Neodymium (0.1)	35,700,000
Silicon metal	Solar panels, semiconductors, silicon anodes in future Li-ion batteries.	2.8	6.6	31,600,000
Tantalum	Capacitors and other electronics.	0	0	1,093,692
Titanium metal	Light-weight alloys for vehicles and electricity-related structures of all kinds.	3	0.3	180,200,000
Vanadium	Stationary redox batteries (large-scale energy storage).	0	0	6,938,400

* Strategic raw materials (considered essential to the green energy transition) are listed in bold italics.

Here, we provide lists of the most important CRMs for the Nordic countries compared against selected non-CRMs (Table 2.4). These lists were considered to prioritise work in the collection and harvesting of existing databases on primary and secondary resources, such as the ProSUM and other EU-commissioned anthropogenic environmental inventories, as well as other mineral deposit databases (e.g., the Fennoscandian Ore Deposit Database, FODD, and the European Geological Data Infrastructure, EGDl):

Table 2.4. Comparative list of CRMs vs non-CRMs for the Nordic countries.

Most important CRMs for the Nordics	Most important non-CRMs for the Nordics
Aluminium	Ash
Boron	Basalt fibres
Cobalt	Cadmium
Copper	Chromium
Feldspar	Gold*
Hafnium	Iron
Lithium	Lead
Manganese	Molybdenum
Natural graphite	Sliver
Nickel	Tellurium
Niobium	Zinc
PGM	
Phosphate rock	
Phosphorus	
REEs	
Silicon metal	
Tantalum	
Titanium	
Vanadium	

* Gold is important for fuel cells, digitalisation and green energy technology. In the context of re-mining, Au can also be considered an important by-product, as it can significantly increase the profitability of a polymetallic ore or waste. Despite these advantages, it is important to note that Au mining can lead to significant waste volumes and is often associated with significant pollution. Waste volumes and therefore sustainability in association/connection with CRMs must be evaluated by the business model of individual gold-producing mines to ensure a net positive outcome for the planet and mankind (Lauri Solismaa, pers. comm., 2024).

Among the non-CRMs mentioned (Table 2.4), ash, often a by-product of combustion, is utilised in the construction industry for creating environmentally friendly building materials such as lightweight concrete. Basalt fibres, sourced from volcanic rock, are valued for their potential in reinforcing wind turbine blades, due to their high strength and resistance to harsh environmental conditions. Cadmium and tellurium are crucial in the manufacture of cost-effective thin-film solar panels, which provide an alternative to traditional silicon-based panels. Silver and gold are indispensable in solar cell conductors and electronic components within renewable energy systems due to their superior electrical conductivity. These precious metals are also essential in the production of advanced hardware for generative AI, necessitating high electrical conductivity and thermal resistance for efficient processing. These materials collectively help to drive the efficiency and expansion of both renewable energy technologies and innovative advancements in generative AI.

2.9 Mineral and metal production in the Nordic countries

In this section, we review some of the key mines and mineral or metal production sites and discuss information on the key historical operations to primarily understand which mines have probably produced significant mining waste in the Nordics. Some countries, such as Iceland, do not have significant mining to warrant the evaluation of mining waste. However, they produce waste from some of their smelting operations that could be valuable, as it contains CRMs such as silicon metal and aluminium or copper and cobalt. This general overview of the production history in the Nordic countries provides context for some of the case studies on mining waste documented in the following sections. This work also illustrates some of the research that was conducted to identify mining waste localities subsequently included in the ND.

2.9.1 Mining and mineral processing in Denmark and Greenland

Denmark, the Faroe Islands and Greenland make up the Kingdom of Denmark (KD). Denmark has several industrial mineral mines in operation and produced petroleum and natural gas in the Danish area of the North Sea. Its industrial mineral production includes clay (bentonite), cement, lime, peat and diatomite. The latter accounts for approximately 17% of the global production of 440,000 t/yr. (USGS 2024). Denmark is known to produce half of its energy from renewable sources (50% from wind turbines and 3% from solar). In section 3.7, the importance of urban waste management is exemplified, and its use in energy production further supports more sustainable practices involving waste reduction and recycling.

If we consider the other parts of KD, mineral commodities are not expected to play a role in the Faroese economy unless significant resources are identified. At present, some potential only exists for coal and aggregates. Greenland is a self-governing part of KD. Officially known as Kalaallit Nunaat, it is the largest island in the world, being roughly 28% of the total area of Australia and covering 2.16 million square kilometres. Greenland has a variety of mineral resources, such as coal, copper, gold, graphite, ilmenite, molybdenum, iron ore, lead, nickel, precious stones, REEs, silver, titanium, uranium and zinc. Several exploration and prospecting licenses were granted by the government to increase international interest in a wide variety of minerals as part of Greenland's Mineral Strategy 2020–2024 (MMRGG 2020). Currently active mines are the White Mountain anorthosite mine (the largest anorthosite occurrence discovered) and the Aappaluttoq corundum mine. Several historical mines have been developed to exploit cryolite, used in the flushing of aluminium smelters, in a lead–zinc deposit (Black Angel mine, Black Angel Mining Group owned), and a recently active gold mine (Nalunaq mine owned by Amaroq). Some of these operations have been significant and had protracted mining for several decades. During its operation (1973–1990), the Black Angel mine, located in the central-western part of Greenland, actively produced lead and zinc, and the disposal of its tailings occurred in adjacent seawater as slurry transported to a fjord. This practice was common to Greenland and caused significant pollution of seawater proximal to the fjord inlets where the disposal practice occurred. The mine production varied between 600,000 and 735,000 tonnes per year, with estimated production of 135,000 tonnes of zinc concentrate and 35,000 tonnes of lead concentrate (Thomassen 1991).

2.9.2 Mining and mineral processing in Finland

Finland has a well-developed mineral industry; this comes from a strong tradition in providing services to mining companies globally. There is also a good geological knowledge base, ore potential and infrastructure, which have led to important mineral discoveries and mining developments. The increased commitment to the energy transition is also resulting in new infrastructure and mines focused on the extraction of CRMs such as lithium (Sibanye Stillwater, formerly Keliber Oy). In 2023, Finland ranked as a top producer of chromium, mica, phosphate rock, peat, selenium, sulphur and talc (USGS 2024).

In 2024, Finland has 12 metal mines with active or in pre-production stage operations (Cr, Ni, Au, Ag and Li represent some of the major commodities of interest at these sites). Among non-metals, it is relevant to report that Finland has active phosphate rock mining in the Siilinjärvi deposit, a top phosphate resource for fertiliser production in Europe. Finland's metallic mineral mines are mostly privately owned by international corporations, although the Finnish government holds stakes in some of the major operations, such as the Talvivaara Ni, Zn, Cu, Co, U deposit. Other significant projects include the Hannukainen iron ore project, the Hautalampi cobalt–nickel mining project, the Keliber lithium operation (Keliber Oy, now a subsidiary of the Sibanye-Stillwater Group) and the Otso (Laiva) gold mine (2021 Otso Gold Oy) in Raahe. Another operation that targeted the restarting of mining activities is the Pahtavaara gold mine (Rupert Resources Ltd.).

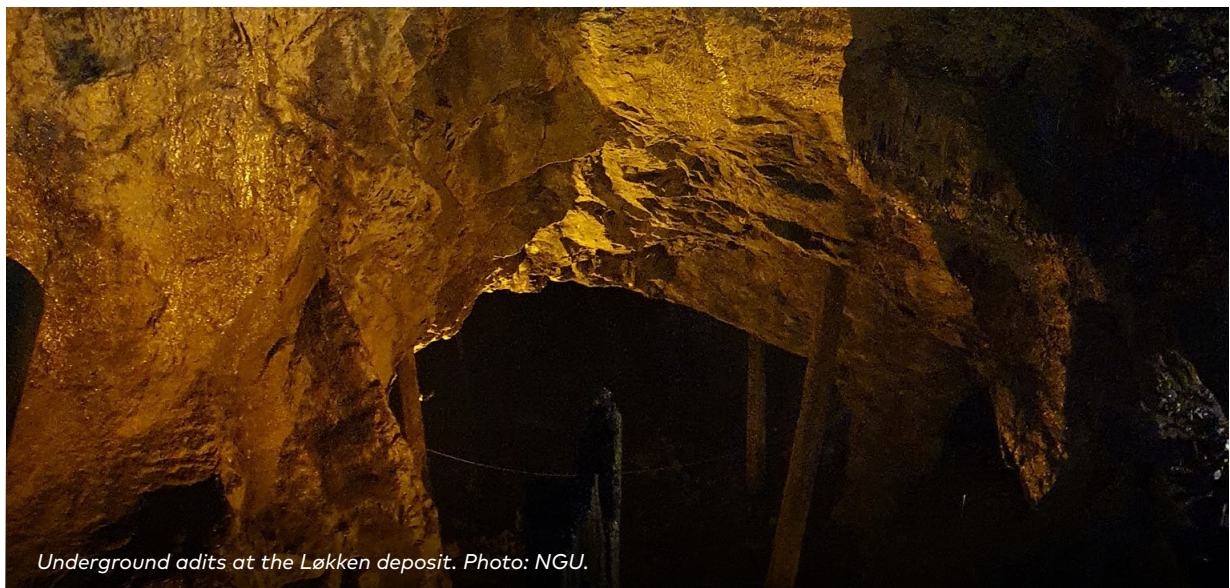
Finland exports products mainly directed to European countries (e.g., Germany and Sweden) and the USA. There are important ore refinement operations that involve CRMs, such as cobalt (Kokkola, Europe's leading refinery, 15,000 metric tonnes per yr, Umicore Finland Oy).

The most important active mining operations include the Kevitsa Cu–Ni open-pit mine, owned and operated by Boliden Mineral AB (Sweden). The mine produces cobalt, copper, gold, nickel, platinum and palladium. Volumes of milled ore are in the order of 9.5 Mt/yr, with plans for Boliden to further increase capacity. Another important Cu operation now under closure is the Pyhäsalmi Mine (First Quantum Minerals Ltd., Canada). The mine produced 8,000 mt yearly of copper metal, which progressively wound down to 3,000 mt/yr due to depletion in the final stages of operation (First Quantum Minerals Ltd. 2019). Similarly, the Kylahti mine also experienced a reduction in Cu output due to lower grades, which led to its planned closure by Boliden in 2020 (Boliden AB 2019, Malmberg 2019, GTK 2024).

The most important Au operation in Finland is the exploitation of the Suurikuusikko deposit (one of the largest Au resources in Europe, currently owned by Agnico Eagle Mines Ltd.) at Kittilä, which in 2023 produced a reported 234,402 oz of Au bullion (Agnico Eagle Mines Limited 2024). In 2023, the deposit had reserves of 3.6 Moz Au. The production of Au started in 2009, and it is expected to continue well into 2034. Agnico Eagle Mines expanded the capacity of the mill in 2021, which led to a current mill capacity of 2 Mt/yr of ore and 0.7 Mt/yr of waste. In 2019, another Au mine, the Kaapelinkulma open pit (owned by Dragon Mining Ltd.), started producing ore that is processed at the Vammala plant, 65 km to the east of Kittilä. The plant also processes ore from other Au mines operated by Dragon Mining Ltd., the Jokisivu and Orivesi operations, which are both active producers, although the Orivesi mine

is in the closure phase. This mine produced 3.3 Mt of ore with a respectable Au grade of 7.1 g/t (Dragon Mining Limited 2023). Another important CRM actively mined in Finland is Ni. The Talvivaara mine and metal production plant, located in Sotkamo, Kainuu, and owned by Terrafame Ltd. produced most base metal ores in Finland (Ni, Zn and by-product Co and Cu) using the bioleaching method. In 2022, the mine produced 31,550 tonnes of Ni, which is above the 30,000 t/yr target the company had set (Terrafame Oy 2023). The nickel ore produced at Talvivaara, Kevitsa and Kylylahti is processed at the Harjavalta smelter in the western part of Finland. Another commodity produced in Finland is silver. Although not classified as a CRM, silver is crucial for the green energy transition due to its superior conductivity, which is essential for solar panels, wind turbines, electric vehicles and energy storage solutions. The only primary producer is the Silver Mine in Sotkamo. In its most recent operations, the mine processed approximately 478,000 tonnes of ore, resulting in the production of about 1,411,000 ounces of silver, 3,048 ounces of gold, 909 tonnes of lead and 1,857 tonnes of zinc (Sotkamo Silver AB 2024). The concentrates are delivered to Boliden's smelters at Kokkola in Finland and Rönnskär in Sweden (Kajastie 2019). During the past few years, the Geological Survey of Finland (GTK) has identified several new mineral deposits. The likelihood of additional discoveries has been enhanced with the entrance of foreign companies into the Finnish mineral industry. This has already resulted in the discovery of major deposits since the 2000s (Sakatti Ni–Cu–PGE and Rompas–Rajapalot Au–U) and recently (Ikkari and Heinä South findings, see Thomas et al. 2023), and the discovery of REEs at the Korsnäs carbonatite-associated deposit (Prospech Ltd.).

Notable tailings facilities such as the Terrafame, Kittilä and the now-closed Pyhäsalmi mine exemplify the country's commitment to sustainable mining and innovative tailings management. Terrafame enhances safety and environmental standards by employing bioleaching for metal extraction. Kittilä employs advanced technologies for tailings stabilisation, prioritising environmental safety and community engagement. Pyhäsalmi, recognised for its use of paste backfill technology, effectively managed waste and minimised environmental impacts.



Underground adits at the Løkken deposit. Photo: NGU.

2.9.3 Mining and mineral processing in Iceland

Mining has not been one of the main drivers of Icelandic trade, and minor gold and coal exploration and mining is reported (Eilu et al. 2021). However, Iceland is represented by a complex geological framework, being at the intersection of a major structure, the Atlantic rift, and centred on a major hot spot. Its unique geological setting renders it a natural attraction for its vulcanism and has favoured the development and flourishing of the geothermal energy industry, which represents a unique supply of renewable energy. This has led to the establishment of raw material processing facilities because of the country's strategic position in the Atlantic, which favours trade with both the EU and the USA.

Although devoid of significant fuel or metallic mineral reserves, Iceland exports ferrosilicon and silicon metal given its accessible renewable energy and modern facilities. Iceland was among the top exporters of silicon and aluminium in the period 2020–23 (Statistics Iceland 2020, USGS 2024). More than 70% of its exported goods went to EU countries.

Considering its aluminium industry, some of the most important smelters are the Fjaröaál smelter at Reydarfjörður, which had a production capacity of 344,000 metric tonnes per year (t/yr), a smelter in Grundartangi owned by Century Aluminum Co., with recorded production of 317,000 t/yr, and the ISAL smelter in Straumsvík owned by Rio Tinto Alcan Inc., with a production capacity of 212,000 t/yr. Ferrosilicon production is reported for Elkem Iceland ehf (Elkem AS) at Akranes and has a production capacity of 120,000 t/yr.

In recent years, new smelters have been constructed that produce silicon with processes that are more energy efficient if compared to aluminium refineries. Silicon metal production is more sustainable given that it is less energy intensive than aluminium recycling. The PCC Bakki Silicon is a relatively new silicon metal plant located in Bakki near Husavík, which started production in 2019. It uses renewable energy sources to process quartzites in electric arc furnaces with a production capacity of 32,000 t/yr of silicon metal, an important CRM for semiconductor chip and wafer manufacturers.

The smelting of silicon produces slag residue with impurities such as aluminium, calcium and other metals, depending on the purity of the quartzite supplied to the furnace. Several studies have considered the option of recovering these CRM metals from the slag produced annually (Larsen & Kleiv 2017). Approximately 10 to 25% of the production of a smelter is represented by slags, dominantly containing silicon, aluminium, calcium and other metals (e.g., this might include gallium, Þorvaldur Þórðarson, pers. comm., 2024).

2.9.4 Mining and mineral processing in Norway

Norway ranks 4th in the production of silicon, accounting for 6% of world production, and 10th in the production of titanium ore (ilmenite), accounting for 5% of world production (USGS 2024). Norway also produces other essential metals and minerals (aluminium and graphite) to produce batteries and other technology such as wind turbines and solar cells. The country has a relatively high GDP if compared to EU countries, which can be attributed to its leadership in the production of petroleum and natural gas. It ranked 3rd in gas exports globally in 2024 (Norwegian Offshore Directorate 2024, Norwegian Petroleum Directorate 2024). Norwegian mineral trade mostly includes EU countries such as Germany, the Netherlands and Sweden. Outside the EU, it trades with China and the USA.

Focusing on the metal producers, some of the most important operations include the Tellnes mine (Titania AS) for titanium ores and Rana Gruber an iron ore (non-CRM) producer in central Norway. The Tellnes mine reached full capacity in 2017, exploiting a Fe–Ti deposit that was discovered 63 years earlier (in 1954) thanks to geological mapping and an aeromagnetic survey. Production started at Tellnes in October 1960, while the Storgangen operation (70 Mt ilmenite ores) continued until 1965. Since then, all of Titania's mining activities have been confined to Tellnes. Production from the Tellnes open pit in 1999 accounted for 2 million tonnes of ore and 1.6 million tonnes of waste rock, resulting in approximately 580,000 tonnes of ilmenite concentrate. More recent production data for the Tellnes mine have not been publicly disclosed (Geological Survey of Norway 2024a).

Another important deposit worth considering is the Engebø deposit, which is one of the largest unexploited rutile deposits in the world (98 Mt), with a rutile grade (TiO₂, 3.51%) that is among the highest if compared to existing producers and projects under development. The deposit is also rich in high-quality garnet. The owner, Nordic Mining, commenced early construction of mine facilities at Engebø in April 2022 (Nordic Mining, 2022).

In 2018, the most significant mineral production increases were for graphite (45%), cobalt (refinery, 20%), silicomanganese (16%) and zinc (smelter and primary, 11%). Some production decreases occurred for ferromanganese (18%) and titanium mineral concentrate (12%). Of these, it is worth considering flake graphite, because of its major importance as an anode material in battery production. A major Norwegian producer is Mineral Commodities Ltd. at Skaland, which has been active in increasing production (10,000 tonnes in 2022) and product quality at the Trælen deposit.

Another important project is led by Nussir ASA, a company established in 2005 to develop the Nussir copper deposit (considered the largest Cu deposit in Norway), which has recently started the construction of a mine after receiving approval from the government. In late September 2014, Nussir reported an updated resource estimate for its Nussir project located above the Arctic circle. The resources for the project totalled 66 Mt of copper ore. Along with the resource estimate for Ulveryggen totalling 7.7 million mt, total resources at the Nussir project were at 74 Mt (USGS 2021). Increasing international demand for metals and minerals has resulted in increased interest in Norway's rich mineral resources, including those of calcium carbonate, flake graphite, nickel,

olivine, high-purity quartz, titanium minerals, rare earths and phosphate. This has resulted in the discovery of major REE deposits (the Fen Complex) in the southeastern part of Norway and phosphate-rich prospects/deposits in its southwestern counterpart (Norge Mining). The construction of a new copper mine by Nussir in Norway's northern municipality of Kvalsund is expected to increase the production of copper in Norway, reversing the declining trend of copper production in recent years.

Norway holds substantial potential for the recovery of CRMs from tailings resulting from mining operations. This potential is especially pronounced in inland VMS deposits such as Løkken, Joma and Sulitjelma which are rich in lead, zinc, copper and cobalt (Pb–Zn–Cu–Co) or Fosdalen, a VMS with significant past production and limited Cu–Co potential. Furthermore, the extensive fjord systems present potential opportunities for recovering minerals through the dredging of marine tailings in fjord-contained dams (Asmund & Johansen 1999, Geological Survey of Norway 2024b).

2.9.5 Mining and mineral processing in Sweden

Sweden is one of the EU's leading ore and metal producers. Mineral deposits and mines are concentrated in three significant regions of the Fennoscandian Shield: (1) the Skellefte mining district, enriched in base (Zn–Pb–Cu) and precious metals (Au); (2) the Norrbotten region, characterised by iron deposits and copper, gold and silver deposits; and (3) the Bergslagen region, dominated by iron and base metal deposits. Several deposits are also located in other areas of Sweden (Goclawska 2022, SGU 2024a). In 2023, Sweden was among the top iron-producing nations globally (USGS 2024). Although iron is not a CRM on the EU list, it is a commodity that leads to significant volumes of waste globally (e.g., Hrinchenko & Yushin 2019). A variety of iron deposits can contain by-products (Högnelid 2021). Important Swedish iron oxide apatite deposits (IOA or Kiruna-type) contain significant concentrations of REEs, P and F (e.g., Kirunavaara, Malmberget and Per Geijer), whereas skarn-type ores do not share a similar CRM potential (e.g., Kaunisvaara and Dannemora). Other commodities produced by Sweden are base and precious metals (zinc, lead, copper, silver and gold; e.g., Aitik is the most significant producer in the country of polymetallic ores). Other special metalloids that are commonly co-products of copper refinement include selenium (not currently produced in Sweden) and tellurium (USGS 2024). These elements are not included as CRMs on the 2023 list; however, they are useful in solar cell film production, and tellurium is also used in thermoelectric materials for energy production.

Recent mineral exploration programmes in Sweden have seen substantial activity from major mining companies. In 2023, exploration efforts were particularly active in the Norrbotten and Västerbotten counties, with Boliden Mineral AB and Luossavaara-Kiirunavaara AB (LKAB) continuing as key players. Boliden has been focusing on production-related exploration at its Garpenberg mine, while also engaging in strategic partnerships for exploring other assets, such as the Tomtebo property (District Metals Corp. & Boliden Mineral AB 2023, Swedish Geological Survey 2023). Tomtebo contains similar host rocks, structure, alteration and mineralisation styles to the Garpenberg, Falun and Zinkgruvan mines. LKAB's intensive exploration work in recent years has meant that the mineral resources at mines in Svappavaara, Gällivare and Kiruna are nearly four times higher than in 2019.

In 2023, the country had 12 metal mines in production (Geological Survey of Sweden 2024). Iron is dominantly produced by LKAB, the leading iron ore producer in the EU; production in 2023 amounted 25.3 Mt of iron finished products (Luossavaara-Kiirunavaara AB 2024). This is followed by Kaunis Iron AB, another producer with a major operation in the Norrbotten region: the Kaunisvaara (Pajala) deposit. Kaunis Iron has been producing iron concentrate since 2018, and production in 2022 amounted 5.83 Mt of enriched ore concentrate (Ljiljenstolpe et al. 2023).

Boliden is an essential company in Sweden, known for producing a range of metals, including copper, gold, zinc lead and silver. The main operations of Boliden in Sweden are concentrated in several key locations in the Norrbotten and Dalarnas regions. The Aitik mine, one of Europe's largest copper mines, is a major part of their operations. Aitik has recorded production declines over the last five years, and in 2023, copper metal amounted to 64,236 tonnes (McGimpsey et al. 2023). This is a significant decline if compared to the 2018 production of 99,000 tonnes.

Other important sites include the Boliden area mines such as Kankberg, Kristineberg and Renström, along with the Garpenberg mine. Additionally, Boliden controls significant processing facilities, including a smelter and refinery at Rönnskär.

Lundin Mining also contributes notably to Sweden's metal production landscape. Lundin Mining owns and operates through a subsidiary the Zinkgruvan mine located in southern Sweden, which is a significant source of zinc, lead and copper. Lovisagruvan is a small lead and zinc producer in the Bergslagen district, which in 2023 produced ca. 34,000 tonnes of ore.

Copperstone Resources is revitalising the Viscaria mine near Kiruna, aiming to make it one of the largest copper producers in northern Europe by 2026. Copperstone Resources also conducted mineral resources estimates of historical tailings at Viscaria. This project highlights the growing demand for copper, driven by the global transition towards renewable energy sources.

The primary production in Sweden generates several waste streams that may be used as secondary resources, especially if they contain CRMs. The iron oxide apatite deposited waste contains significant CRMs, such as REEs and P, which LKAB is already planning to recover as co-products (Högnelid 2021). Considerable potential is also associated with major copper operations, from which, for example, Au, Ag, Mo and Co could potentially be extracted as by-products from waste materials.

3 Investigations of the CRM potential and other factors influencing waste management and re-mining in the Nordic countries

In this section, several case studies are presented to evaluate the CRM potential of historical mining waste sites and active (waste producing) operations in some of the Nordic countries. Investigations considered different geological, geochemical, mineralogical, geophysical and local community studies and led to a better characterisation of mining and industrial waste, providing an indication of the potential recovery of metals from different types of waste. Further to this, social perceptions were examined to extend the dimension connected with environmental and social components of mining projects, to improve sustainable practice.

3.1 Environmental, social and governance issues associated with Finnish mine tailings

Work Package 2 (WP2) of the Nordic Sustainable Minerals (NSM) project consisted of an assessment of the CRM potential of secondary resources contained in old, current and future tailings. WP2 included four case studies from Finland (Table 3.1) that considered the social license to operate (SLO) and environmental, social and governance factors in the classification of secondary resources (ESG).



Hydrothermally altered pillow lava flows at the Løkken deposit. Photo: NGU.

Table 3.1. The Finnish mine tailings-related case studies and their characteristics. SLO = Social license to operate; ESG = Environmental, social and governance.

PROJECT AND LOCATION	COMPANY	COMMODITIES	SITUATION	SLO AND ESG ISSUES
AIJALA, SALO	Aijala Invest Oy	Cu, Zn, Pb, Au, Ag	Closed old mine, plans to remine tailings, under a feasibility study	Sulphides with acid mine drainage, contamination of soil and waters with heavy metals. Public acceptance for re-mining but concerns about impacts and risks.
RAPASAARI AND SYVÄJÄRVI, KAUSTINEN	Sibanye Stillwater Keliber Oy	Li	Mining license, mine construction, starting production soon	No organised opposition, but complaints about water quality monitoring
OTANMÄKI, KAJAANI	Otanmäki Oy	V, Ti	Closed old mine, applying for license to remine	Finnish Important Bird Area (FINIBA) in the old tailings settling pond, second homes on the lake shore and concerns about impacts on them
TALVIVAARA, SOTKAMO	Terrafame Oy	Ni, Cu, Co, Zn, U	Operating mine (bioleaching)	Environmental problems and its gypsum pond leakage formed the key event of the mining debate in 2012. After that, it was taken over by the state.

The reuse of mining waste has been considered an important circular economy action in Finland (Pokka et al. 2024). Although the attitudes of authorities and the industry are positively changing regarding the reutilisation of mining waste (Kinnunen & Kaksonen 2019), and attitudes towards old mines have been investigated (Kivinen et al. 2018), little is known about local attitudes towards the re-mining of the tailings. Research on the topic has focused on economic, technical and environmental aspects (Edraki et al. 2014, Markovaara-Koivisto et al. 2018, Maest 2023). Although it has been considered that the local community attitudes can be critical towards re-mining (Suppes & Heuss-Aßbichler 2021), it has also been supposed that such attitudes would be positive, because harmful substances are removed and valuable metals are recovered, reducing their environmental impact (Figueiredo et al. 2019). In any case, local people are recommended to be contacted, informed, and their attitudes surveyed before any re-mining project starts (Figueiredo et al. 2019).

The NSM project assessed the situation of the Finnish case studies regarding the social license to operate (SLO), i.e., public acceptance (Thomson & Boutilier 2011), and related environmental, social and governance (ESG) issues. Regarding the Kaustinen, Otanmäki and Talvivaara projects, the assessment was based on a literature review and protest event analysis (PEA; Koopmans & Rucht 1999). PEA is a systematic study of the online media coverage of a project. Its purpose is to detect any sign of dispute or controversies from the media record. This was applied by using Meltwater media analysis software. The keyword was a project or company name. The whole media record for each project, including that of social media, was surveyed between January 2023 and April 2024. Any critical media report was then selected and scrutinised to determine potential contentious issues and actors.

Unfortunately, the attitudes of local people were not assessed by the public participatory geographical information system (PPGIS, e.g., Kivinen et al. 2018), as was initially proposed. This was because no training for this was available. Instead, the attitudes of the local community towards re-mining were examined via a poll in Aijala. Further to this, in Otanmäki and Kaustinen, environmental impact assessments (EIAs) are ongoing, which also include social impact assessment (SIA). SIA is carried out using statements, interviews and surveys, and its results also reflect local attitudes towards a project. Therefore, the authors did not want to interfere in this process with an additional poll. For instance, Talvivaara is a well-known case of past environmental problems and dispute, and its history and current situation were examined via a literature review and PEA.

A categorisation of the SLO status of projects was also created for database purposes. In addition, the legal constraints for re-mining in Nordic countries were considered. The activities of NSM WP2 on SLO and ESG issues and their main results related to these case studies are summarised below.

3.1.1 Aijala

The old Aijala underground mine is located in the Kisko region, Salo municipality, southern Finland. It produced Cu, Zn, S, Au and Ag from 1941–1961 and was operated by the Finnish state-owned mining company Outokumpu Oy. The process plant operated from 1952–1974, and it also received ore from the Metsämonttu mine nearby and Ni–Cu ores from the Telkkälä mine. Tailings were stored in Aijala (Fig. 3.1), and they contain sulphides, which cause acid mine drainage (AMD) and heavy metal contamination of waters and soil (Tornivaara et al. 2018, 2020). In 2018, there was also a collapse of its underground tunnels, which released contaminated water onto surrounding crops.

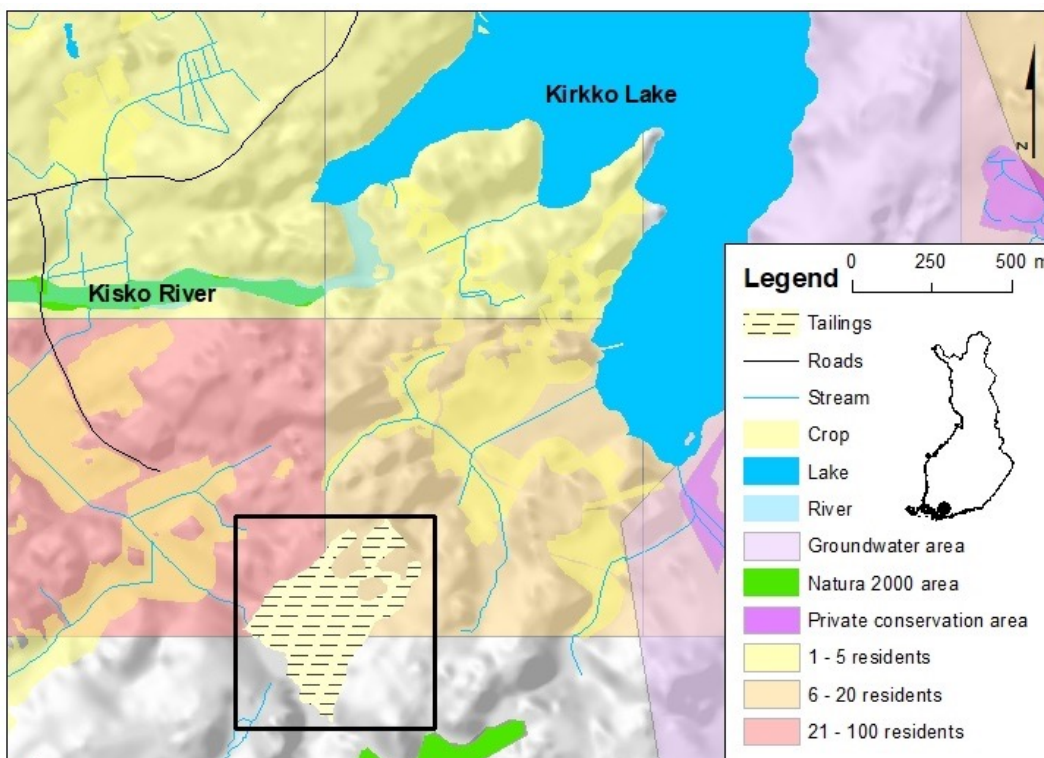


Figure 3.1. The Aijala tailings area with its associated land use and population density.

The Aijala tailings have been studied regarding their characterisation, resource estimation and remediation (Markovaara-Koivisto et al. 2018, Tornivaara et al. 2018, 2020). The tailings are located in an area surrounded by residents (6 to 100) and between the Natura 2000 areas of the Kisko River to the north and a protected mire to the south (Fig. 3.1). Drainage from the tailings is towards the Kisko River and from there into Lake Kirkkojärvi.

The mine and tailings areas of Aijala are owned by a private company, Aijala Invest Oy. It plans to remine the tailings in association with a major mining company (Salin 2023). They are performing a feasibility study, and the start of the project and license application will depend on its results.

Beyond a poll on local attitudes regarding re-mining, the WP2 activities in the Aijala region have included a site visit together with a representative of Aijala Invest Oy as a guide, and meetings with the municipality, environmental authorities (KAJAK Project), a local environmental non-governmental organisation (ENGO) and the community. A public event was organised by the NSM project at a secondary school in Salo on 25 October 2023. Presentations on the subject were given by GTK, the environmental authorities, Aijala Invest Oy and the local ENGO. This was covered in a local newspaper article (Salin 2023). Subsequently, a poll on the issue was advertised in local newspapers and through e-mails to stakeholders. This resulted in another local newspaper article with an interview (Poutanen 2023).

3.1.1.1 Poll

A questionnaire was prepared for the survey containing 17 questions, some of which were to be answered in writing. Some of the simple yes/no questions also included a complementary question to be answered in writing. The main purpose of the poll was to reveal local attitudes towards re-mining. However, other questions were also asked regarding the perception of mining, tailings and their environmental impacts in the region, knowledge of the permit requirements and the significance of tailings and re-mining. The poll was arranged electronically using Webropol software and by e-mail and mail at the end of 2023. Altogether, 854 questionnaires were sent by mail to addresses with Aijala and Kisko postal codes.

3.1.1.2 Results

In total, 114 answers were received, of which 71 were electronic and 43 by mail. A report on the electronic answers was generated by Webropol, while those received by mail were extracted from the paper versions. Apparently, this was the first time that local community attitudes had been surveyed regarding the re-mining of tailings. As the complete results of the poll will be published elsewhere, only some of the main findings are revealed below.

Rather critical opinions were expressed towards mining in written answers, but most of the respondents supported re-mining. However, there was also concern about its risks and environmental impacts. Nevertheless, it is uncertain whether and how much the public event about the issue and subsequent local newspaper articles influenced such opinions. In any case, public awareness of tailings and their importance was raised, which was also one of the goals of the project. However, most of the respondents had no idea about the permit requirements for re-mining.

3.1.2 Kaustinen

Kaustinen is located in western Finland. Lithium was already found there in the 1950s, but it took decades before exploration proceeded. Beyond Rapasaari and Syväjärvi (Fig. 3.2), the prospects of Länttä, Outojärvi and Emmes also belong to the same project. The lithium mine project is held and managed by the South African–Finnish company Sibanye Stillwater Keliber. The company has a mining permit and aims to start lithium production from pegmatites in 2024.

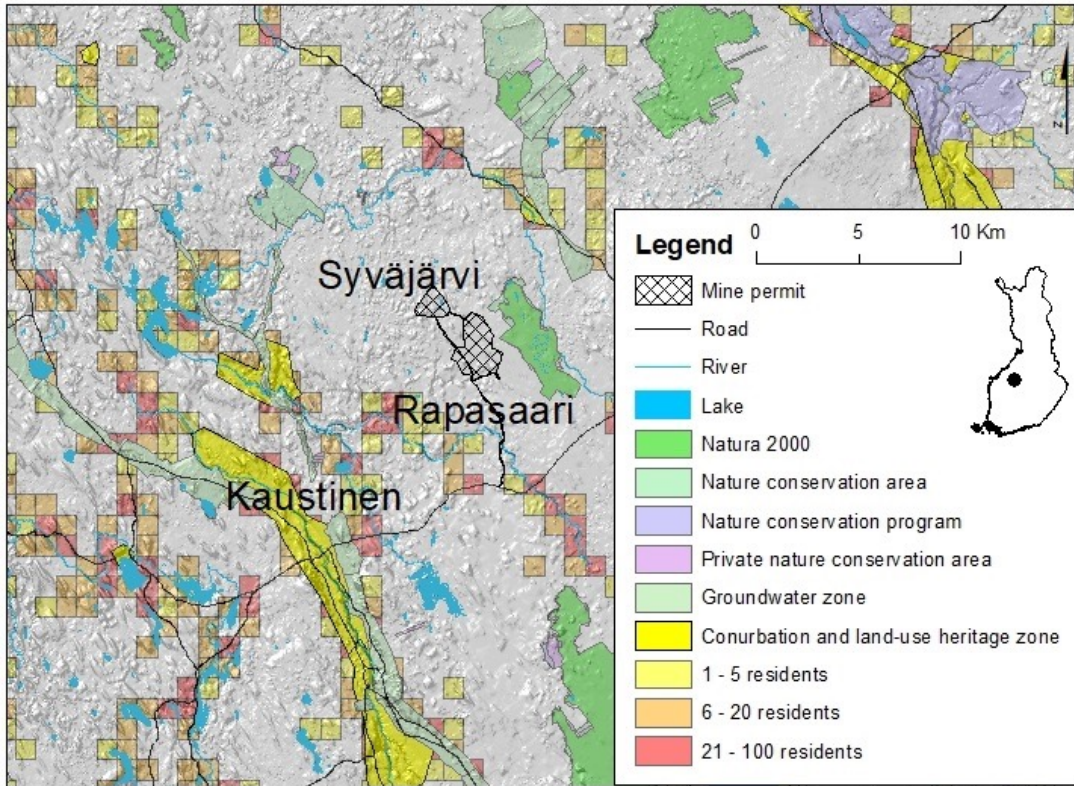


Figure 3.2. The Kaustinen lithium project with its associated land use and population density.

According to a recent mapping of the Finnish mining and mineral exploration disputes (MEDs) by Eerola (2022), western Finland is almost devoid of mining and mineral exploration disputes, although it is a focus of intense lithium exploration. This also concerns Kaustinen, although the mine sites therein are close to a Natura 2000 area (Fig. 3.2), and protected areas are among the sensitive contexts from which MEDs generally emerge in Finland (Eerola 2022). The mine site is located far from residential areas (Fig. 3.2) and the project's media cover has been quite positive; the results of the PEA are presented in Table 3.2.

Table 3.2. Online media record of the Kaustinen project 2023–2024.

COMPANY/PROJECT/ LOCALITY	TOTAL MEDIA HITS	CRITICAL MEDIA HITS
KELIBER/KAUSTINEN	290	6

The critical media hits were mostly found in social media (X), where the same message regarding “a mine to be set up in the middle of deer forest” was reposted a couple of times. Although no organised opposition was detected, non-governmental organisations and local landowners, as well as fishery associations, have appealed against the permit approvals (Vihanta 2019, Holopainen 2021), but the appeals have mostly been rejected by a Supreme Court ruling (Holopainen 2021).

As identified by Leino et al. (2023), the lack of a perception of environmental injustice towards the project and its permit process among the locals might explain the lack of opposition. The region has also been a stage for agriculture, forestry, peat production and fur creation, and its coastal area is industrial. These livelihoods might also influence such attitudes. Nevertheless, care should be taken in mine construction and operation, as any misconduct could result in controversies and opposition. Since its beginning, Keliber Oy has been developing and testing circular economy applications for its tailings and waste rocks with good results (Pokka et al. 2024).

3.1.3 Otanmäki

The Otanmäki Fe–Ti–V deposit is located ca. 2 km north of the village of Otanmäki and 37 km west of the city of Kajaani (Fig. 3.3). The mine operated from 1953–1985 and Otanmäki Mine Oy plans to reopen it, intending to remine the Ti-containing mineral ilmenite from old tailings. An ongoing EIA is being conducted and expected to be completed in 2024.

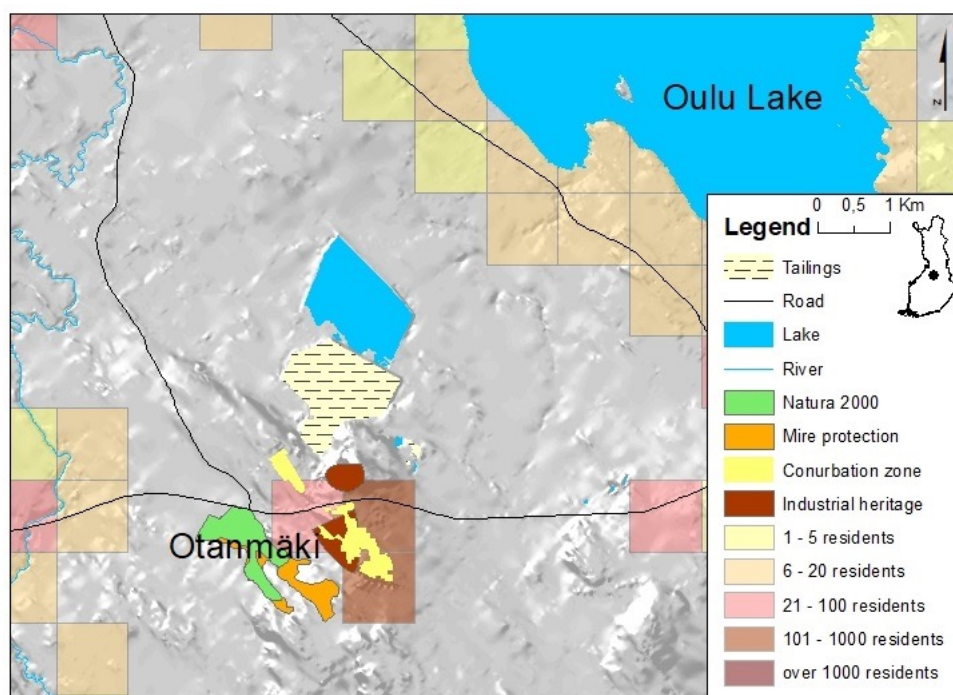


Figure 3.3. Otanmäki area with its associated land use and population density.

Previous studies on the Otanmäki ilmenite tailings project have focused on resource evaluation, pilot plant tests and tailings mineralogy. The EIA report provided information on the project's current state and its future perspectives. The tailings have been classified according to the United Nations Framework for Classification (UNFC). Eerola (2024) focused on clarifying social and environmental risks within the UNFC E-axis. A summary of the report findings is given below. A more extended discussion of environmental, social and governance (ESG) issues is also provided in Eerola et al. (2024).

With current knowledge, the potential environmental risks associated with the re-mining activities were evaluated as minor, but more studies are needed regarding, for example, the quality of mine tailings forming in the re-mining process. Risks that have been noted include the fluctuation of water levels, effluent leaks, the lowering of surface and groundwater quality, and the downstream mobilisation of tailings. Additionally, mining activities might impact local biodiversity through noise, vibration and dust. The protection of the old settling pond (Bird Pond), a Finnish Important Bird Area (FINIBA), needs to be carefully considered. As the EIA process advances, a better understanding of the likelihood of these risks, their consequences, and the measures aimed at minimising them will be gained. Table 3.3 presents the results of the PEA for 2023.

Table 3.3. The media record regarding the Otanmäki deposit and its mining and re-mining project in 2023–2024, obtained using Meltwater media analysis software.

COMPANY/PROJECT/ LOCALITY	TOTAL MEDIA HITS	MEDIA HITS RELATED TO THE PROJECT	CRITICAL MEDIA HITS
OTANMÄKI	155	46	3

Media hits and mentions related to the project (46) were found in local and national online newspapers and media, magazines, social media and online debates. The covered topics are related to the mine, the planned railway from Otanmäki to a vanadium factory to be built in Raahe, the history of the mining community, including a museum exhibition, as well as investigations and EIA of the re-mining project. The only mentions that can be considered as critical towards the project (3) concern statements given for the EIA programme published by newspapers related to concerns about possible environmental impacts on the Bird Pond and second homes on the shores of Lake Oulujärvi (e.g., Rönty 2023, Fig. 3.3). However, no signs of any organised opposition were detected, and most of the media record is quite positive towards the project. In 2024, 8 non-critical mentions about Otanmäki were detected.

3.1.4 Talvivaara

Talvivaara is a polymetallic sulphide deposit found in the 1970s in Sotkamo, Kainuu Province, northern Finland (Fig. 3.4). However, its exploitation became feasible only through bioleaching, which was applied therein during the 2000s. Talvivaara enjoyed a positive public image until its environmental problems and association with uranium became evident from 2010 onwards (Sairinen et al. 2017). In 2012, its gypsum pond leak formed the key event of the ongoing national mining debate. Because of its environmental problems, the Talvivaara company went bankrupt and was taken over by the state-owned Terrafame Oy. Under public administration, the environmental impacts of the mine were

controlled and reduced. However, concerns regarding the emission of effluents into Lake Nuasjärvi (Fig. 3.4) have been presented by second homeowners and ENGOs (Eerola 2022). Because of its past reputation, Talvivaara still influences the national debate on mining in a negative way.

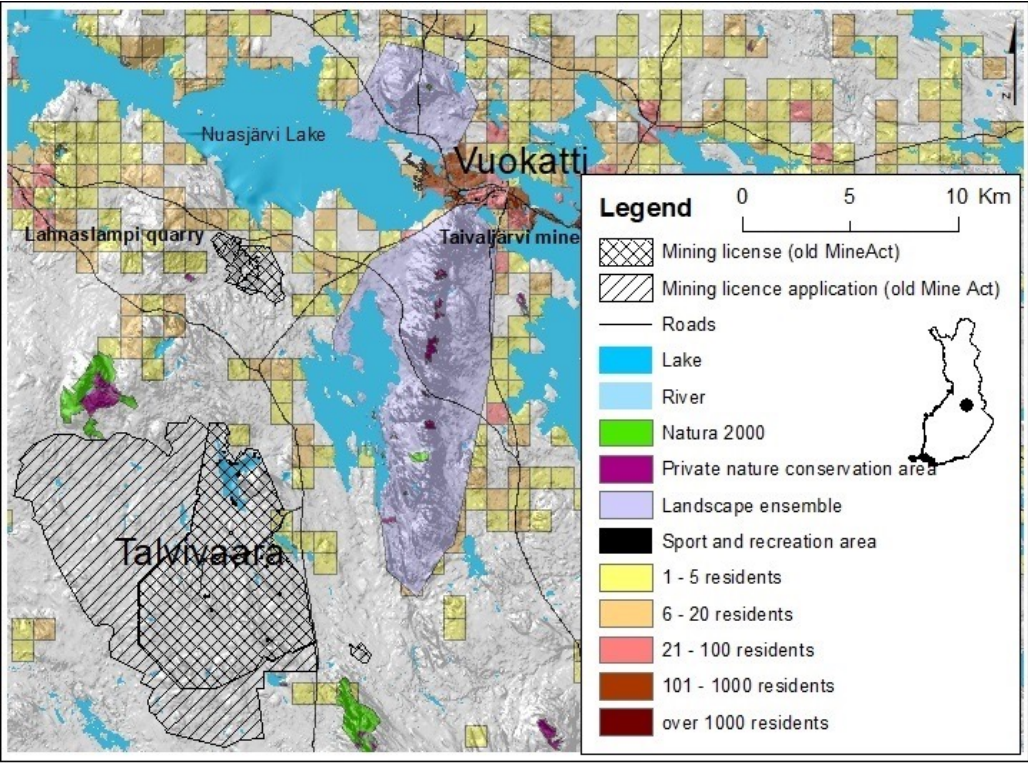


Figure 3.4. Talvivaara mine area with its associated land use and population density.

Surprisingly, despite its environmental problems, dispute and reputation, Talvivaara has been an example of a harmonic co-existence of tourism and mining; Vuokatti is a popular resort in Sotkamo (Fig. 3.4). According to Harju (2019), this has apparently been due to the strategy of tourism entrepreneurs, who avoid calling attention to the mine and its problems to prevent harm to their own business.

Table 3.4. The online media record regarding the Talvivaara mine 2023–2024.

COMPANY/PROJECT/LOCALITY	TOTAL MEDIA HITS	CRITICAL MEDIA HITS
TALVIVAARA/TERRAFAME	1703	139

In 2023, there were 1087 media hits, of which 66 were negative. The corresponding figures for 2024 were 616 and 73. The negative social media posts mention Terrafame's performance in 2022 and the sustainability issues of various mining companies, including Terrafame. According to Pokka et al. (2024), the production process of Terrafame potentializes the efficient exploitation of metalliferous side streams. However, its demonstration is demanding and constrained by a slow permitting process.

3.1.5 Project categorisation regarding public acceptance

A classification scheme for SLO was created by Eerola (2023), which was adapted from the Environmental Justice Atlas' conflict intensity levels (Temper et al. 2015). The scheme is based on four categories of conflicts, from the most to the least intense: high, medium, low and latent/nonexistent, for which numerical values of 3, 2, 1 and 0 are respectively given. Their characteristics are presented in Table 3.5, together with a classification of the case studies. The case studies presented here can be considered as latent/nonexistent (0) (Table 3.5). However, Talvivaara already occupied a medium level (2) (Eerola 2022).

Table 3.5. Conflict intensity levels of the Environmental Justice Atlas (Temper et al. 2015), and numerical values given for them by Eerola (2023).

INTENSITY	CHARACTERISTICS	NUMERICAL VALUE	CASE STUDY CLASSIFICATION
HIGH	Violence, mass mobilisations, mass arrests (conflict)	3	
MEDIUM	Street protests, visible organisation (dispute)	2	
LOW	Some organisation (dispute)	1	
LATENT/ NONEXISTENT	No visible organisation	0	Aijala Kaustinen Otanmäki Talvivaara

3.1.6 Legal aspects related to the re-mining of tailings

A poll in Aijala revealed that the respondents knew little about the legal requirements or permit process for the re-mining of tailings. Their characteristics in Nordic countries are summarised in Table 3.6 and described below.

Table 3.6. Regulation, permits and authorities concerning the re-mining of tailings in Nordic countries. As Iceland has no metal mining, it is omitted.

COUNTRY	FINLAND	GREENLAND (DENMARK)	NORWAY	SWEDEN
LEGISLATION	Environmental Act	No information	Planning and Building Act	Environmental Act (unclear if the Mining Act is applied)
PERMITS	Environmental	No information	Construction and Environmental permits	Environmental permit
AUTHORITY	Environmental authority	No information	Environmental Protection Agency	Environmental Protection Agency

- As tailings are considered to be waste, their permitting has been a quite complex issue in Finland (Vesa 2021). However, the permitting of the above-described Otanmäki tailings project is being considered under the environmental permit applied for from the respective authority. For this, an EIA is needed, such as described above. As Otanmäki is the first case in Finland, it will probably form an antecedent for further permitting.
- In Sweden, the situation regarding the regulation and permitting of re-mining appears to be far from clear (SGU & Naturvårdsverket 2023). The Environmental Act regulates the activity to a large extent, but it is not clear whether the Mining Act should be applied.
- Norway has allowed the deposition of tailings in fjords and coastal marine areas (Høyli & Jakobsen 2022). Due to favourable topography Norway has tailings deposited below sea level. Tailings are considered as waste in Norway and the regulation of this is a resource is not clear. Producers work actively on valorisation of their tailings.
- Greenland's tailings have also been deposited in fjords. Apparently, there are no considerations regarding the re-mining of tailings.
- As Iceland had no large-scale metal mining operations, there are no tailings to be remined.

3.1.7 Conclusions regarding the Finnish case studies

Four Finnish cases were examined regarding their ESG and SLO issues: Aijala, Kaustinen, Otanmäki and Talvivaara. Re-mining is planned for the tailings of Aijala and Otanmäki, whereas Talvivaara and Kaustinen have considered other circular economy solutions.

A poll in Aijala revealed that the respondents accept re-mining but have concerns about its environmental impacts. The Otanmäki project appears to not be opposed, although complaints have been made regarding its EIA programme. Apparently, despite complaints, the project in Kaustinen has local acceptance. Although Talvivaara formed the key event of the mining debate with its gypsum pond leakage, it is now better managed and co-exists harmonically with tourism.

Information on tailings, their re-mining, risks, environmental impacts and permit requirements is needed among the local population. Authorities, research institutions and industry have an important role in raising public awareness of the subject and its importance. In similar cases, local attitudes towards re-mining are also recommended to be surveyed and the associated land use to be mapped regarding sensitive contexts that may conflict with the activity.

A framework for SLO classification was created and all the case studies reported here are in the latent/nonexistent dispute (O) category. However, care should be taken to perform re-mining sustainably and to avoid causing adverse environmental and social impacts. Any misconduct or poorly managed project might negatively impact on the image of this emerging activity and industry.

To potentialize re-mining effectively in Nordic countries, its regulation and monitoring need to be clarified and established. The Otanmäki project represented an important step by setting the first case in Finland with a clear permitting process under the environmental act. It is a good example to be followed.

3.2 Grängesberg & Yxsjöberg case studies on tailings

3.2.1 Grängesberg

Grängesberg is home to the largest iron oxide apatite (IOA) deposit in Bergslagen, Sweden. Mining commenced in 1783 and continued, except for several shorter suspensions, until 1989. The deposit is generally divided into two ore fields: Exportfältet and Risbergsfältet. In total, 153 million tonnes of ore were extracted from the mines at Grängesberg, 133 million tonnes from Exportfältet and 20 million tonnes from Risbergsfältet (SGU 2024a). The ore had an average grade of 49.7% iron and 5.2% phosphate at Exportfältet, and 43% iron and 0.4% phosphate at Risbergsfältet. Most of the ore was extracted from the late 1800s and onwards, when methods were developed for the efficient removal of phosphorus from the ore. Remaining indicated and inferred resources include 148 million tonnes at 40.0–42.5% iron and 0.7–0.98% phosphorus (Grängesberg Iron AB 2014). Analyses of drill core sections have revealed up to 0.56% REE and 0.32% vanadium (SGU 2024b); however, no resource estimates are available for these commodities.

Much of the ore was extracted as lump ore and only produced waste rock as mining waste, of which a total of 74 million tonnes has been generated over the years (SGU 2024a). Lower-grade ore was initially processed in several smaller plants and ca. 1 million tonnes of tailings were deposited in a near-mine pond. In the early 1950s, two larger processing plants were built, from which a total of 14 million tonnes of tailings were deposited in three tailings dams (SGU 2024a): Hötjärnen, Jan Matsdammen and Svandammen (Fig. 3.5).

3.2.2 Yxsjöberg

Yxsjöberg, located about 25 km southwest of Ludvika in Bergslagen, is the largest producer of tungsten in Sweden and accounted for more than 90% of the total mined tungsten tonnage in the country (Bergman 2012, SGU 2024a). Yxsjöberg is a tungsten–copper skarn deposit carrying scheelite, chalcopyrite and fluorite as the main economic minerals. Three main ore bodies have been mined: Kvarnåsen, Nävergruvan and Finngruvan (Ohlsson 1979). The deposit was originally mined for copper in the early 18th century and tungsten mining started in 1917, with intermittent production until closure in 1989. The last period of activity was from 1971–1989. Most of the ore that was processed on-site was extracted from the Yxsjöberg deposit, but nearby smaller mines such as Sandudden and Wigström also supplied ore to the concentrator.

The average head grade of the processed ore was 0.27% tungsten and 0.16% copper (SGU 2024a). According to Rothelius (1957), the ore also contained 5–6% fluorite. Analyses of drill core sections have revealed that the ore is enriched in several critical and strategic metals, such as bismuth, beryllium and indium (Hallberg & Reginiussen 2019, 2020).

Small-scale ore processing of tungsten at Yxsjöberg began in 1918 but was abandoned in the 1920s due to falling prices (Hübner 1971). Altogether, 5.3 million tonnes of ore were processed at Yxsjöberg during the period 1938–1989. Early ore processing was by hand picking and gravimetric separation. Flotation processing commenced in 1977, which significantly increased the recovery of tungsten. The production of 79,000 tonnes of tungsten, copper and fluorite concentrate has generated more than 5 million tonnes of tailings, which were deposited in two separate repositories (see section 3.2.5, Fig. 3.6).

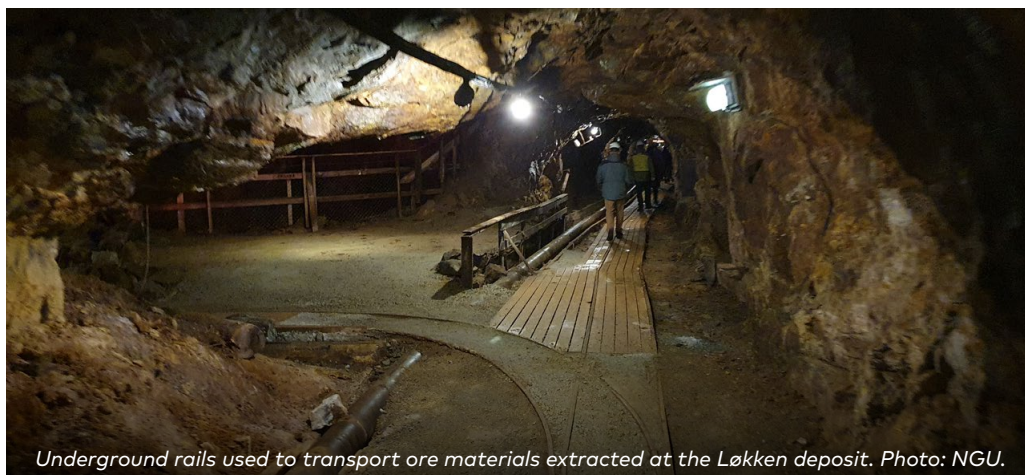
3.2.3 Methods and sampling

Mining waste (tailings and waste rock) has been subject to systematic sampling and characterisation by SGU since 2016. The data presented for the Grängesberg and Yxsjöberg case studies are compiled from Hallberg & Reginius (2018, 2019, 2020) and Casey et al. (2024). In addition, 30 additional samples were collected from the Yxsjöberg tailings in May 2023 as part of this project to complement the previously produced data.

Near-surface samples of tailings were retrieved using an *Edelman auger* hand drill from ca. 50–100 cm depth below the surface. Due to the high groundwater table at the Grängesberg and Yxsjöberg tailings dams, this is generally below the oxidised horizon. A mechanised drill rig was also used to sample the entire depth of tailings at 1-metre intervals.

Geophysical measurements were taken using several methods with the aim of establishing the thickness of and, if possible, compositional differences within the tailings (Casey et al. 2024). The methods used were electrical resistivity tomography (ERT), induced polarisation (IP), radiomagnetotelluric (RMT) sounding and towed transient electromagnetics (tTEM), which all characterise the electric conductivity of the tailings material.

The areal extent of the tailings ponds was estimated from historic aerial photographs, which together with a depth model derived from geophysical measurements was used to calculate the total volume of tailings. Measurements of the bulk density allowed for the calculation of total masses. The calculated tonnages are in good agreement with numbers deduced from historic production data (SGU 2024a), which confirms that most of the deposited tailings remain in the ponds.



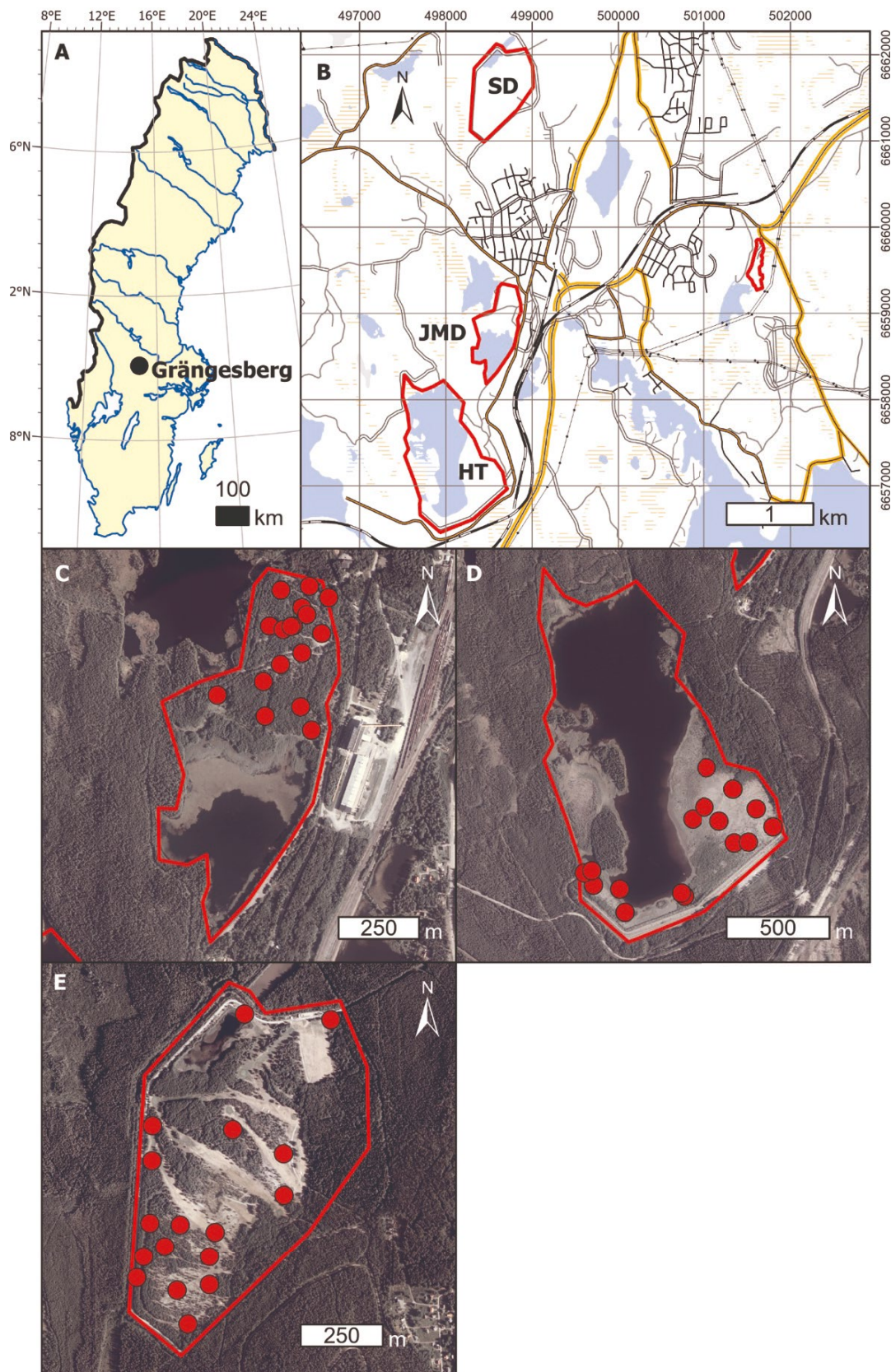


Figure 3.5. A. Map of Sweden with the location of Grängesberg marked. B. Map of Grängesberg with the location of tailings dams marked with red polygons; JMD = Jan-Matsdammen, HT = Hötjärnen, and SD = Svandammen. C–E. Aerial photos (Lantmäteriet) of Jan-Matsdammen, Hötjärnen and Svandammen, with sample locations marked with red dots.

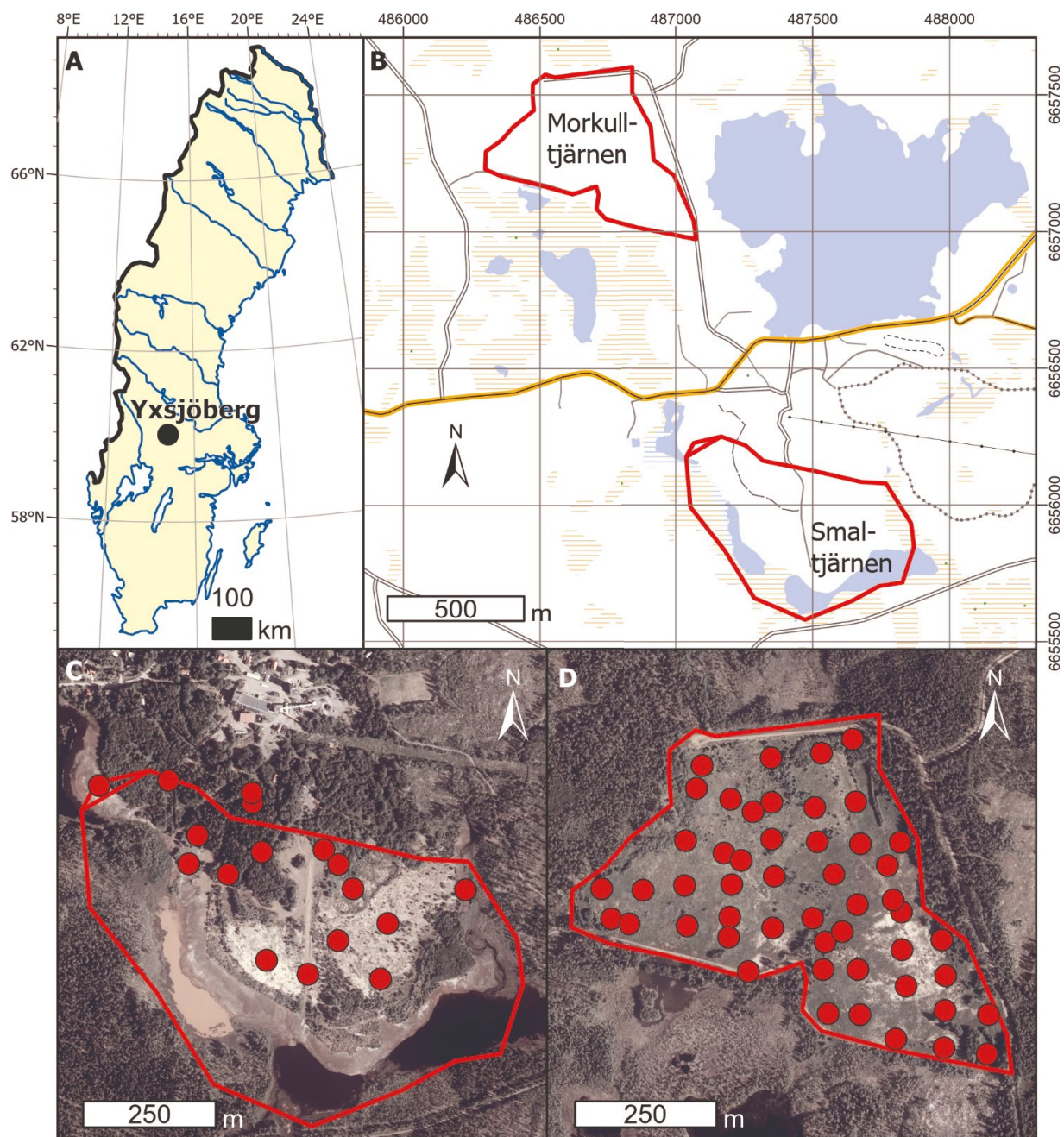


Figure 3.6. A. Map of Sweden showing the location of Yxsjöberg. B. Map of the Yxsjöberg area with the location of the two tailings repositories (red polygons); C–D. Aerial photos (Lantmäteriet) of tailings at Smaltjärnen (C) and Morkulltjärnen (D). Red dots indicate sampling locations.

Waste rock was sampled from heaps using a sampling strategy developed by Sädbom & Bäckström (2018). Following this strategy, a heap is subdivided into 15–20 smaller areas, from which a composite sample is retrieved by randomly collecting 25–50 rock pieces. The area and volume were estimated from aerial photographs and LIDAR data.

Tailings and waste rock samples were sent to ALS Laboratories for sample preparation and multi-method wide spectrum major and trace element analysis. Five W-rich tailings samples from Yxsjöberg were analysed by scanning electron microscopy (SEM) X-ray diffraction spectroscopy to qualitatively determine the mineralogy of individual grains.

The CRM/SRM potential was calculated by multiplying non-weighted average concentrations obtained from geochemical analyses with the total amount of tailings or waste rock contained in the respective repositories. It is emphasised that these are not industry standard mineral resource estimates and should only be seen as rough approximations of the resource potential.

3.2.4 Critical and strategic mineral potential of Grängesberg

The three tailing storage facilities (TSFs) in Grängesberg together contain ca. 14 million tonnes of tailings. Sampling demonstrated elevated concentrations of several critical raw materials, and according to a simplified resource estimate, the TSFs together may host ca. 170,000 tonnes of phosphorous (P), 24,000 tonnes of rare earth elements (REE+Y) and 6,000 tonnes of vanadium (V; Table 3.7).

Table 3.7. Grängesberg CRM/SRM potential. All figures are in tonnes. None of the figures can be considered as proper resource estimates.

DEPOSIT	WASTE	P	REE+Y	V
JAN-MATSDAMMEN TAILINGS	2,550,000	58,000	4,700	940
HÖTJÄRNE TAILINGS	8,400,000	81,000	16,000	4,600
SVANDAMMEN TAILINGS	3,120,000	29,000	2,800	400
TOTAL TAILINGS	14,070,000	168,000	23,500	5,940
WASTE ROCK	6,400,000	26,000	3,300	1,600
TOTAL CRM/SRM POTENTIAL	20,470,000	194,000	26,800	7,540

3.2.4.1 Jan-Matsdammen

Jan-Matsdammen is the oldest of the three main TSFs in Grängesberg, at which the deposition of tailings started in ca. 1955 and ceased in ca. 1975. The TSF volume has been calculated from geophysical measurements to be 1.43 million m³, which corresponds to 2.55 million tonnes of tailings (Casey et al. 2024). SGU sampling and drilling campaigns revealed elevated concentrations of phosphorus (0.51–2.97%), REEs (0.6–0.22%) and vanadium (117–662 ppm) for a total of 42 samples. A recent scoping study for re-mining of these tailings estimates an indicated resource of 3.46 million tonnes tailings grading 2.38% phosphorus and 9.69% iron (Lindholm 2022), largely agreeing with the data collected by SGU.

3.2.4.2 Hötjärnen

Hötjärnen is the largest TSF at Grängesberg. Deposition of tailings commenced in the early 1970s and terminated in 1989. Geophysical surveys indicate a total volume of 4.13 million m³, corresponding to 8.4 million tonnes of tailings (Casey et al. 2024). SGU sampling and drilling campaigns show elevated concentrations of phosphorus (0.31–2.70%), REEs (0.10–0.34%) and vanadium (292–1060 ppm) for a total of 57 samples.

3.2.4.3 Svandammen

The deposition of tailings at Svandammen started in the early 1970s and ceased in 1979. The TSF covers ca. 372 000 m², and geophysical measurements indicate a total volume of ca. 2.2 million m³, corresponding to ca. 3.1 million tonnes of tailings (Casey et al. 2024).

SGU sampling and drilling campaigns have demonstrated elevated concentrations of phosphorus (0.69–1.26%), REEs (0.07–0.11%) and vanadium (76–218 ppm) for a total of 32 samples.

3.2.4.4 Waste rock

A total of 73 million tonnes of waste rock was produced during active mining at Grängesberg (SGU 2024a). Most of this material has been used as backfill in the mines or as construction material in nearby TSFs or other infrastructure. Based on LIDAR elevation data, a total of 6.4 million tonnes of waste rock is estimated to remain available in waste piles, for which sampling has revealed elevated concentrations of phosphorus and vanadium (Casey et al. 2024).

3.2.5 Critical and strategic raw material potential of Yxsjöberg

A total of approximately five million tonnes of tailings have been deposited in two repositories at Yxsjöberg. Both repositories show elevated concentrations of tungsten (W), beryllium (Be), bismuth (Bi), copper (Cu), tin (Sn), zinc (Zn) and fluor spar (CaF₂). A rough estimate indicates that the Morkultjärnen repository, which is the focus in this study, contains ca. 2,200 tonnes of tungsten, 1,100 tonnes of copper, 940 tonnes of bismuth, 290 tonnes of beryllium and 780 tonnes of tin.

3.2.5.1 Smaltjärnen tailings

Smaltjärnen, which is the oldest repository at Yxsjöberg, was in use before 1964, and according to available data contains approximately 2.8 million tonnes of tailings. However, the lack of production data for some years prior to 1938 suggests that the real tonnage for Smaltjärnen may be slightly higher than this (Hallberg & Reginiussen 2020). The tailings are not contained within a proper TSF but are directly in contact with Lake Smaltjärnen, and some of the tailings have been deposited in the lake. There were plans for extraction and reprocessing of tungsten from the Smaltjärnen tailings in 1980, but this was not realised (Lindvall 1988). Recent research within the frame of the REMinE project has focused on the environmental impacts of the tailings and the possibility of reprocessing (Hällström et al. 2018, Mulenshi et al. 2019).

Data from eleven samples reveal high concentrations of tungsten (0.06–1.0% W; Hallberg & Reginiussen 2020), suggesting that the recovery was rather poor, as suspected, with the less efficient processing techniques that were used before 1977. Analyses of the Smaltjärnen tailings have demonstrated elevated concentrations of bismuth, beryllium, indium and tin, similar to those seen in drill cores and waste rock from the Yxsjöberg deposit (Table 3.8).

Table 3.8. Approximate CRM/SRM potential at Yxsjöberg (tonnes). Averages, mean, minimum and maximum values for selected elements in Morkultjärnen are also presented. Sn is currently not defined as a CRM/SRM by the EU, but is included due to the elevated grades of this metal in the waste. Note that the calculation of metal contents in Smaltjärnen tailings is based on 11 near-surface samples only. None of the figures can be considered as proper resource estimates.

DEPOSIT	WASTE	W	Cu	Bi	Be	Sn
MORKULTJÄRNEN TAILINGS	2,200,000	2,200	1,100	940	290	780
SMALTJÄRNEN TAILINGS	2,800,000	7,500	3,800	1,550	350	1,600
TOTAL TAILINGS	5,000,000	9,700	4,900	2,490	640	2,380
WASTE ROCK	644,000	450	170	75	30	60
TOTAL CRM/SRM POTENTIAL	5,644,000	10,150	5,070	2,570	670	2,440

Analyses of tailings at Morkultjärnen, Yxsjöberg (n = 85):

ELEMENT	AVERAGE	MEDIAN	MIN	MAX
Be (ppm)	122	122.5	39.3	223
Bi (ppm)	425	409.5	143	1010
Cu (ppm)	470	419	60	1410
In (ppm)	3.6	3.6	1.4	6.1
Sn (ppm)	325	323	171	447
W (ppm)	904	621	245	7060
*F (%)	3.37	3.33	2.73	4.52
*CaF ₂ (%)	6.9%	6.8	5.6	9.2

*F content and calculated CaF₂ are based on 6 analyses from 5 drillholes.

3.2.5.2 Morkultjärnen tailings

During 1969–1989, tailings from Yxsjöberg were deposited within a TSF at Morkultjärnen, located to the north of the mine and concentrator. From aerial photographs and LiDAR data, the surface area of the impounded tailings is calculated to be approximately 245,000 m². The surface gently slopes from the highest level at the southeast corner at (320 masl) to the lowest (306 masl) in the northwest. The location of the discharge point, as inferred from historic aerial photographs from 1975 (Fig. 3.7, A), was in the eastern margin of the dam, although it is very probable that both its location and the direction of flow have changed over time and with the filling of the repository.

The results of drilling and geophysical investigations indicate a general thickness between 5 and 12 metres, with the largest depth found in the central part of the repository. The surface material in the southern and eastern parts is dominated by medium to coarse sand, whereas the northern and western sides comprise more fine-grained material. Based on production statistics, the total tonnage contained at Morkultjärnen has been estimated to be 2.4 million tonnes (Hallberg & Reginiussen 2020), which is in good agreement with a recent calculation of 2.2 million tonnes based on new depth and volume data (Casey et al. 2024).

Previous geochemical surface sampling and drilling campaigns by SGU have produced 55 samples. Of these, 14 are surface samples and 41 samples are from 5 different boreholes (5–10 m deep). Although high concentrations of tungsten have been detected in a few surface samples of fine-grained material in the northwest, it has been inferred that tungsten is generally enriched in coarse sand in proximity to the point of discharge due to the proximal accumulation of scheelite (Casey et al. 2024).

The current project produced an additional 30 near-surface samples, and the geochemical dataset now consists of 49 evenly distributed near-surface samples that cover most of the repository area (Fig. 3.7, B).

The average concentrations of selected elements in the full dataset (85 samples) are presented in Table 3.8. Highlights are as follows: tungsten (904 ppm), copper (470 ppm), bismuth (425 ppm), tin (325 ppm), zinc (267 ppm) and beryllium (122 ppm). No definitive spatial pattern can be seen in the variation of grades for various elements. However, the new data acquired in the current project confirm that the distal NW part of the dam is enriched in tungsten and indicate that the distribution of scheelite, which is the main tungsten-carrying mineral, may be more complex than previously thought. One explanation is that the discharge points have changed over time, leading to new enrichment areas for tungsten. Tungsten exhibits rather unsystematic variation in the drillholes, but a general trend is increased concentrations at depth and near the surface, with a depletion in the middle of the drillholes. The higher concentration measured at depth probably reflects lower recovery prior to the introduction of flotation (pre-1977). In this context, it is noteworthy that the sample at the bottom of the deepest drillhole has tungsten concentrations that are similar to the average concentration of 11 samples from the older Smaltjärnen repository (Hallberg & Reginiussen 2020).

3.2.5.3 Waste rock

According to production data in MALMdb (SGU 2024a), approximately 644,000 tonnes of waste rock were produced during the mining operations at Yxsjöberg. Recent sampling and analysis of some of the waste rock heaps in the area around the main Yxsjöberg facility and Kvarnåsen has demonstrated elevated concentrations of tungsten, zinc, copper, bismuth, beryllium, indium and tin (Casey et al. 2024), in agreement with the results for analysed ore sections (Hallberg & Reginiussen 2019, 2020).

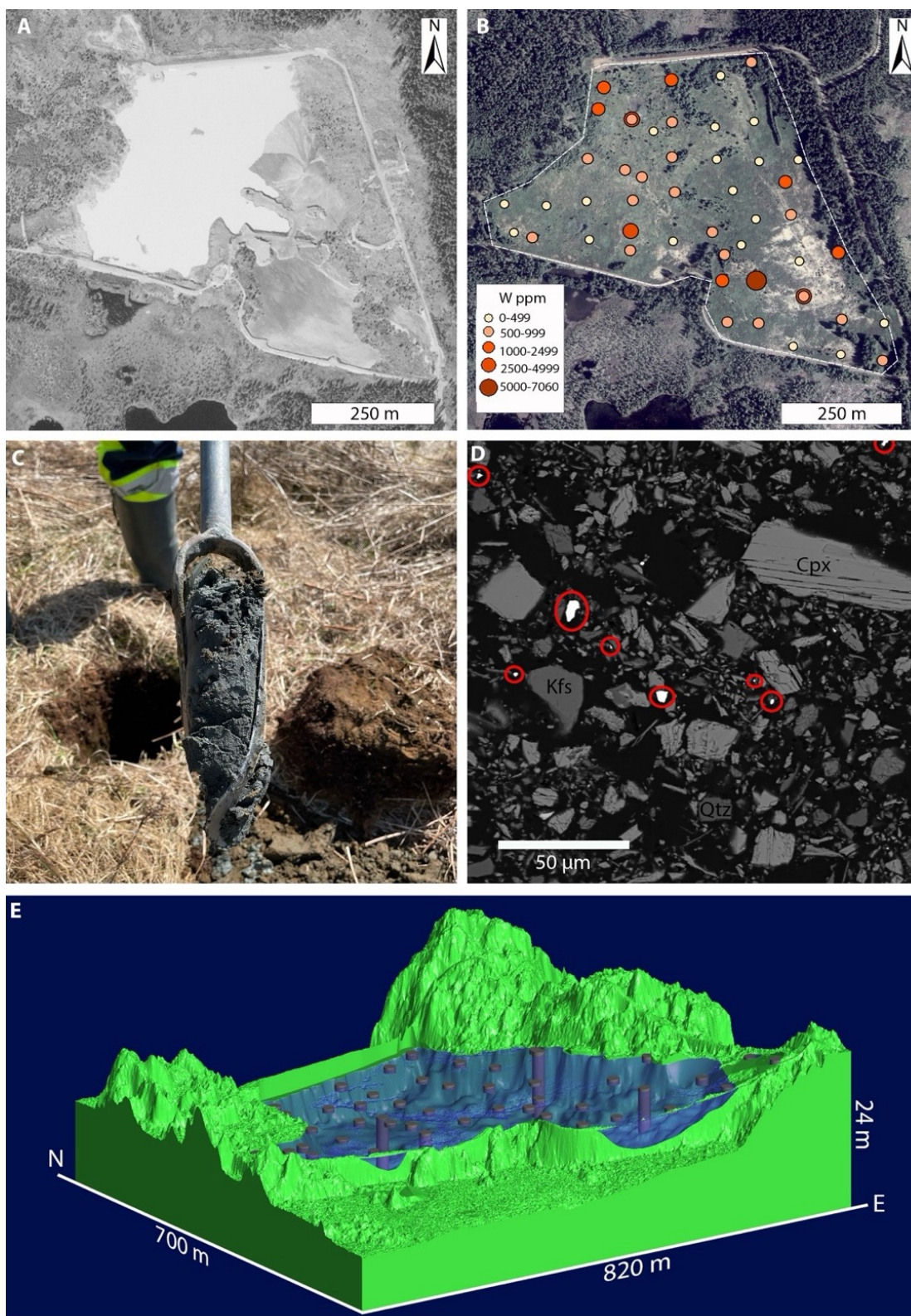


Figure 3.7. A. Aerial photo of tailings at Morkultjärnen from 1975. B. Aerial photo showing sampling locations and corresponding grades of tungsten. (Aerial photos in A–B from Lantmäteriet.) C. Sampling of tailings using an Auger drill (photo: Alexander Lewerentz). D. SEM image of tailings material from Morkultjärnen, which is mainly comprised of clinopyroxene (Cpx), K-feldspar (Kfs) and quartz (Qtz). Scheelite (a tungsten mineral) appears as white specks marked by red ellipsoids. E. 3D model of the Morkultjärnen tailings (transparent blue), underlying sediments and bedrock (green), and drill holes (grey cylinders). Note that the vertical scale is 10 times exaggerated.

3.3 Løkken case study on tailings

3.3.1 Ore geology

The Løkken ophiolite formed in an oceanic back-arc or supra-subduction setting and its volcanic sequence is subdivided into three parts. The lower member, overlying a sheeted dyke complex, comprises an approximately 1-km-thick pile of nonvesicular pillow lavas of normal midocean ridge basalt composition. The ore-hosting, middle volcanic sequence is dominated by voluminous sheet-like basalt flows but also contains local andesitic to dacitic flows. The upper member (0.5–1.0 km thick) is composed of nonvesicular pillowed and massive basalt flows of back-arc basin geochemical affinity, with rhyolite flows and thin units of slate that are present locally.

A reconstruction based on the form of the orebodies and spatial distribution of ore types suggests that sulphide accumulation took place on, or close to, a steep slope or a series of fault scarps on the seafloor, in proximity to a hydrothermal vent field (Grenne & Slack 2005). For details and maps, see Gasser et al. (2021). The Løkken ore body is folded and tectonically disrupted into major and several smaller bodies. At the start of the mining history, extraction took place in the stringer zone (feeder zone) due to the veins enriched in copper. The massive sulphide ore predominantly consists of pyrite with chalcopyrite and sphalerite. Galena, magnetite, hematite and bornite are local minor constituents, and tetrahedrite–tennantite occur as accessories.

3.3.2 Mining and metal extraction history

From the start of mining at Løkken, in 1654, to the mid-19th century, the only metal that was extracted from the Løkken ore was copper. During this period, the ore was roasted, and sulphur was emitted as sulphur dioxide. From the mid-19th century, the production of sulphuric acid in Europe needed raw materials, and pyrite was exported for this use. Mining of pyrite for the production of sulphuric acid started in the 1860s and lasted until 1962. During this time, the ore was crushed, sieved and washed using a collection of different machinery. This was done to separate grain size fractions, and the process was repeated several times. This process produced vast amounts of watery rest material, which needed disposing of. The old tailings was therefore deposited in a settling pond, which was probably initiated in 1909. The pond was constructed along the road and the stream Raubekken, and a wall was built with stone, clay and finally wood. Moraine was placed between the wall and the pond. During the period of first usage, the pond was divided into two basins. Precipitation of copper, zinc and iron was, for a time in the 1940s, conducted using lime, before the clarified water could be released into the stream. The deposit thus differs from other tailings deposits, which consist of material that has gone through an ore refining process. From approximately 1947, the pumping of water and material was discontinued.

Over an extended time period, research was conducted to start the method of producing elementary sulphur and copper matte (30% Cu). From 1963 to 1972, the ore was crushed, and the richer part of the ore was concentrated through flotation. From the start of the 1970s, the market for raw sulphide products decreased in favour of elementary sulphur. From 1974, a new selective flotation facility was opened, and copper and zinc concentrates were produced.

The pyrite fraction could not be sold, so it was deposited, mixed with the tailings in a new tailings storage facility (TSF) (Brøndbo 1997).

The Løkken Cu–Zn pyrite deposit was worked over a period of 333 years (1654–1987), during which approximately 24 million metric tonnes (Mt) of pyritic ore was mined at an average grade of 2.1% Cu, 1.9% Zn, 0.02% Pb, 19 ppm Ag and 0.2 ppm Au (Vokes 1995). The ore is fine grained, and it is necessary with extensive grinding to produce mono-mineralic grains. Studies to improve flotation document that approximately 90% of the grains must be less than 0.038 mm to achieve this (Brøndbo & Ese 1972).

According to Brøndbo (1997), the old tailing deposit contains 138,500 tonnes of material, with a concentration of 19% S, 1.78% Cu and 1.64% Zn. Several attempts have been made to make concentrates of the material, as new flotation processes should be able to treat the product better. The first attempts were conducted in the 1960s to 1970s, when sludge was pumped into the concentration plant. Additional milling of the material was also tried, to increase the surface area and new particle surfaces, but no good results were accomplished.

In 1986–87, another technique was used, transporting several thousand tonnes by lorry, but the sludge products tended to destroy the other flotation process and therefore had to be stopped. In 1987/88, the area was levelled and covered with a layer of 50,000 tonnes of rock.

3.3.3 Geochemical methodology

3.3.3.1 Sampling

Geochemical sampling was conducted in August 2023 using a drill rig and Naver drill (soil screw), extracting material in one-metre vertical sections. Altogether, 141 samples (sample weights 290–3250 g) were collected from nine localities (Figure 3.8). The depth of the tailings varied from approximately 3 to 7 m. The depth of the rock overburden varies over the sampled area from 0–1.5 meters. At all sampling locations, drilling was continued until the drill head hit the bottom of the tailings deposit. The bottom was recognised by underlying coarse, unsorted mass that lay beneath the homogeneous, fine-grained waste material. The coarse material occasionally caused the screw drill to become stuck.

The samples consisted of composite samples that generally represent 30-cm intervals. If changes in material were present, some intervals were shortened. The material was packed in Rilsan bags and stored in cold storage before being sent for analysis. Localities were chosen to avoid any water pipes or electricity cables, but also to represent different filling basins within the deposit, thus representing different time periods. The basins were separated by barriers built out of wood. For example, location 1001 is in a basin that was added at some point in time between 1937 and 1953 (the northernmost basin is not present in an aerial photograph from 1937).



Figure 3.8. Map with sampling locations. For the background, an aerial photograph from 1953 is used.

3.3.3.2 Chemical analyses

In total, 137 samples were sent for chemical analyses at ALS Scandinavia. The samples were air dried and subsequently pulverised at the lab. The analytical packages used were as follows:

ME-ICP06: based on lithium borate fusion and analysis of acid extracted material using ICP-OES. LOI analysed using analytical package OA-GRA05;

ME-MS81: based on lithium borate fusion and analysis of acid extracted material using ICP-MS;

ME-4ACD81: based on extraction by four acids (a combination of nitric acid (HNO_3), perchloric acid (HClO_4), hydrofluoric acid (HF) and hydrochloric acid (HCl)) and analysis using ICP-OES;

ME-OG62: based on ME-4ACD81, but with an override function on high concentrations,

AU-ICP21: based on a gold assay cupel process and analysis using ICP-OES.

3.3.3.3 Data transformation and analysis

The compositional data for each element were manually checked for skewness, and it was decided that a data transformation was needed to open the data. Therefore, before statistical analyses, centred log ratio (clr) transformation was performed in ioGAS.

UMAP is an algorithm that uses different techniques to reduce the data dimensions, combining the parameters in the datasets, and finally visualises similarities and connections. The UMAP plot was also produced with ioGAS.

3.3.4 Geophysics

3.3.4.1 ERT methodology and data capture

Electrical resistivity tomography (ERT) is performed by sending a current between one electrode pair at the same time as measuring the potential and resistance between another electrode pair. Based on the amperage, measured voltage and the position of the electrodes in relation to each other (geometric factor), apparent resistivity is calculated. The equipment used in the surveys consisted of a Lund cable system (Dahlin 1993) and ABEM Terrameter LS (ABEM 2012). Within this study, four multi-electrode cables of 21 electrodes each were connected to the instrument, and a protocol file with electrode configurations was run. The electrode configuration Gradient Plus was used (Dahlin & Zhou 2006).

The resolution of the dataset is controlled by electrode spacing. A smaller electrode spacing results in higher resolution, but this is at the expense of depth penetration. At 5-m electrode spacing, the full outlay will be 400 m long, and the reliable depth penetration will be approx. 50 m. Table 3.9 displays the length, electrode distance and data quality for all profiles.

Table 3.9. Length, measurement direction, electrode distance and data quality of the measured profiles in the form of RMS error.

Name	Method	Length	Direction	RMS Error	Electrode distance
Profile 1	ERT	400 m	South → North	6.7%	5 m
Profile 2	ERT	400 m	South → North	5.9%	5 m

The measured values are apparent resistivity, and these need to be inverted to obtain true resistivity. All data were inverted using Res2DInv (Loke 2017) with robust data constraints. The accuracy along the depth dimension might be somewhat inaccurate. At the surface, the accuracy is equal to the electrode spacing, but this accuracy decreases with greater depth. As seen in Table 3.9, the data quality of all measured datasets is high (<7% RMS error). Ground conditions in all examined areas are very favourable for this type of survey, as the deposited materials provide very low contact resistance between the electrodes and the ground, contributing to the high quality of the datasets.

Previous studies have demonstrated that ERT can be used for mapping tailings landfills based on the pronounced high conductivity of such layers (Markovaara-Koivisto et al. 2018). It is therefore expected that such materials can obtain resistivity values of less than 20 Ωm . ERT can yield the thickness and possibly other properties of the materials in the landfill, such as the concentration of ore materials.

3.3.4.2 GPR methodology and data capture

Ground penetrating radar (GPR), commonly referred to as georadar, is an electromagnetic geophysical technique that can be used to investigate underground stratification. It uses electromagnetic fields to investigate loose dielectric materials to detect structures and changes in material properties within the materials (Davis & Annan 1986). With GPR, the electromagnetic fields propagate as essentially nondispersive waves. The emitted signal travels through the material and is scattered and/or reflected by changes in impedance, giving rise to events that appear similar to the emitted signal (Butler 2005). These reflected signals are registered at the surface and utilised to reconstruct interfaces in the ground. This is achieved by the compilation images, where 1D electromagnetic "soundings" are positioned consecutively to create a uniform 2D image.

In sedimentary materials, electromagnetic waves can only penetrate to a limited depth before being absorbed. Therefore, the depth of penetration is always variable. However, the frequency range in which GPR works is between 1 and 1000 MHz, and the choice of frequency also determines the projected depth of a survey. At lower frequencies, the pulses easily disperse, while at higher frequencies, the signal absorption becomes far too strong and the depth of penetration extremely limited. GPR studies are therefore planned with a frequency selection that compromises the depth of penetration (lower frequencies) with the desired signal resolution (higher frequencies) in relation to the study objectives.

In Løkken, it was expected that the GPR signal would be completely absorbed over the most conductive materials and thus help frame their exposure in an inverse way. This essentially means that even though GPR is unable to reveal the thickness of such layers, it can distinguish them from surrounding geological formations that are more favourable to the propagation of electromagnetic waves such as sand, gravel or weathered rock. GPR interpretations in this context must be based on the distribution of signal amplitude. Therefore, the area was densely covered by 18 profiles (almost 2 km in total length) along paths in the tailings landfill accessible to the GPR system cart. The system used was a PulseEKKO Pro with 100 MHz antennas and 1024 "stacks" (repetitions per trace) offered by the Ultra Receiver unit. Processing was performed using the line section function of the EKKO_project program (Sensors & Software Inc. 2018).

3.3.5 Results and discussion

3.3.5.1 Geochemistry

Table 3.10 presents the results for CRMs and REEs that were analysed, as well as some additional elements. The tailings contain high concentrations of base metals, as the combined median concentrations of Cu and Zn are 4.5%. The median concentration of cobalt is 363 ppm.

Plotting the geochemical results with depth displays the varying concentrations of all elements down profile at all locations.

Within the tailings, certain elements are correlated with each other (correlation coefficient determined after centred log ratio transformation). Coefficients over 0.9 exist for the following ratios: Na₂O:TiO₂ (0.9), K₂O:Rb (0.93), Zr:Hf (0.99), Pb:Ag (0.95), Pb:Mo (0.9), Pb:Au (0.91), Cu:Co (0.94), Zn:Cd (0.95), Ag:Mo (0.94) and Ag:Au (0.95). The close correlation between the rare earth elements is expected.

Figure 3.9 presents boxplots for all common elements analysed between the sampled tailings material, as well as analyses of massive ore from different ore bodies in the Løkken area (N = 45). Only analyses from massive pyrite, chalcopyrite and sphalerite ore samples (unpublished material, NGU) were chosen for this visualisation (samples of "vasskis", fine-grained pyrite in hornfels, were not included). The plot illustrates that the tailings material presents consistently higher median concentrations for all elements, except iron and manganese. It must be noted that the ore samples were analysed using four acids, while some elements for the tailings were analysed from a fused bead (see Table 3.9 for details). Only for certain elements, such as Zr, Hf, Nb, Ta and Ti (Zivkovic et al. 2022), can a lower recovery be expected by applying four acid extraction as opposed to lithium borate fusion. Therefore, the higher concentrations for all other elements can be expected to show comparable results.

In some locations, the material was rusty orange, indicating that oxidation of the material had taken place (locations 1002 0–3.3 m; 1003 0–2.8 m; 1004 0–0.2 m; 1007 0–0.2 m). Preliminary XRD analyses of selected samples indicate a change in mineralogy within these oxidised samples. Even though the oxidised samples contain high metal concentrations, the metal sulphides present in the tailings are not generally evident within these samples.

The UMAP plot in Figure 3.10 separates the samples into clear groups, which reflect different depths within the tailings, or times of sedimentation, showing a difference in mineralogy. For example, the tailings at location 1001 were added as a separate basin at a later stage. Furthermore, the top samples from 1002 and 1003 were oxidised (rusty orange). These samples displayed a differing mineralogy in XRD analyses.

Table 3.10. Overview of selected analysed elements. Concentrations in mg/kg, except for those indicated with a percentage.

Element		Min	1 st quartile	Median	Average	3 rd quartile	Max
CRMs							
Arsenic	As	< 5	200	259	243	296	753
Barium	Ba	4.7	32	56	75	112	474
Cobalt	Co	5	257	363	362	476	760
Gallium	Ga	2.7	13	16	16	19	39
Hafnium	Hf	0.14	0.93	1.2	1.4	1.9	5.6
Magnesium (%)	Mg	0.11	0.82	1.2	1.4	1.7	4.4
Manganese (%)	Mn	0.01	0.03	0.05	0.05	0.06	0.12
Niobium	Nb	0.22	0.83	1.0	1.4	1.4	9.2
Lithium	Li	< 10	10	10	12	10	30
Phosphorus (%)	P	0.01	0.03	0.04	0.05	0.06	0.14
Titanium (%)	Ti	0.02	0.17	0.21	0.20	0.28	0.56
Scandium	Sc	2	8	10	11	14	25
Strontium	Sr	7.9	18	24	45	39	287
Tantalum	Ta	< 0.1	0.2	0.3	0.4	0.5	4.7
Vanadium	V	25	150	181	177	210	415
Tungsten	W	< 0.5	0.9	1.5	1.9	2.4	6.6
REEs							
Lanthanum	La	1	2.6	3.2	4.0	4.3	17
Cerium	Ce	2.9	6	7.2	8.6	8.7	36
Praseodymium	Pr	0.44	1	1.2	1.3	1.4	4.4
Neodymium	Nd	2.4	5.1	5.8	6.5	7.1	22
Samarium	Sm	0.76	1.5	1.8	1.9	2.1	7.1
Europium	Eu	0.18	0.39	0.5	0.5	0.61	2.0
Gadolinium	Gd	0.83	2.0	2.3	2.5	2.7	7.4
Terbium	Tb	0.15	0.34	0.4	0.4	0.48	1.2
Dysprosium	Dy	1.1	2.2	2.7	2.8	3.2	7.6
Holmium	Ho	0.23	0.49	0.58	0.60	0.70	1.42
Erbium	Er	0.54	1.4	1.7	1.7	2.0	4.6
Thulium	Tm	0.09	0.20	0.23	0.30	0.30	0.71
Ytterbium	Yb	0.55	1.3	1.5	1.6	1.9	4.6
Lutetium	Lu	0.08	0.19	0.23	0.20	0.29	0.66
Other elements							
Aluminium	Al	0.69	2.1	2.6	2.9	3.4	7.4
Copper (%)	Cu	0.02	1.8	2.3	2.3	2.8	4.6
Nickel	Ni	14	36	44	45	53	95
Zinc (%)	Zn	0.02	1.2	2.1	2.2	2.6	9.1
Gold	Au	0.001	0.10	0.13	0.10	0.15	0.23
Silver	Ag	0.5	15	18	17	20	36
Cadmium	Cd	0.7	45	79	92	105	383

Ore element concentrations vs. tailings

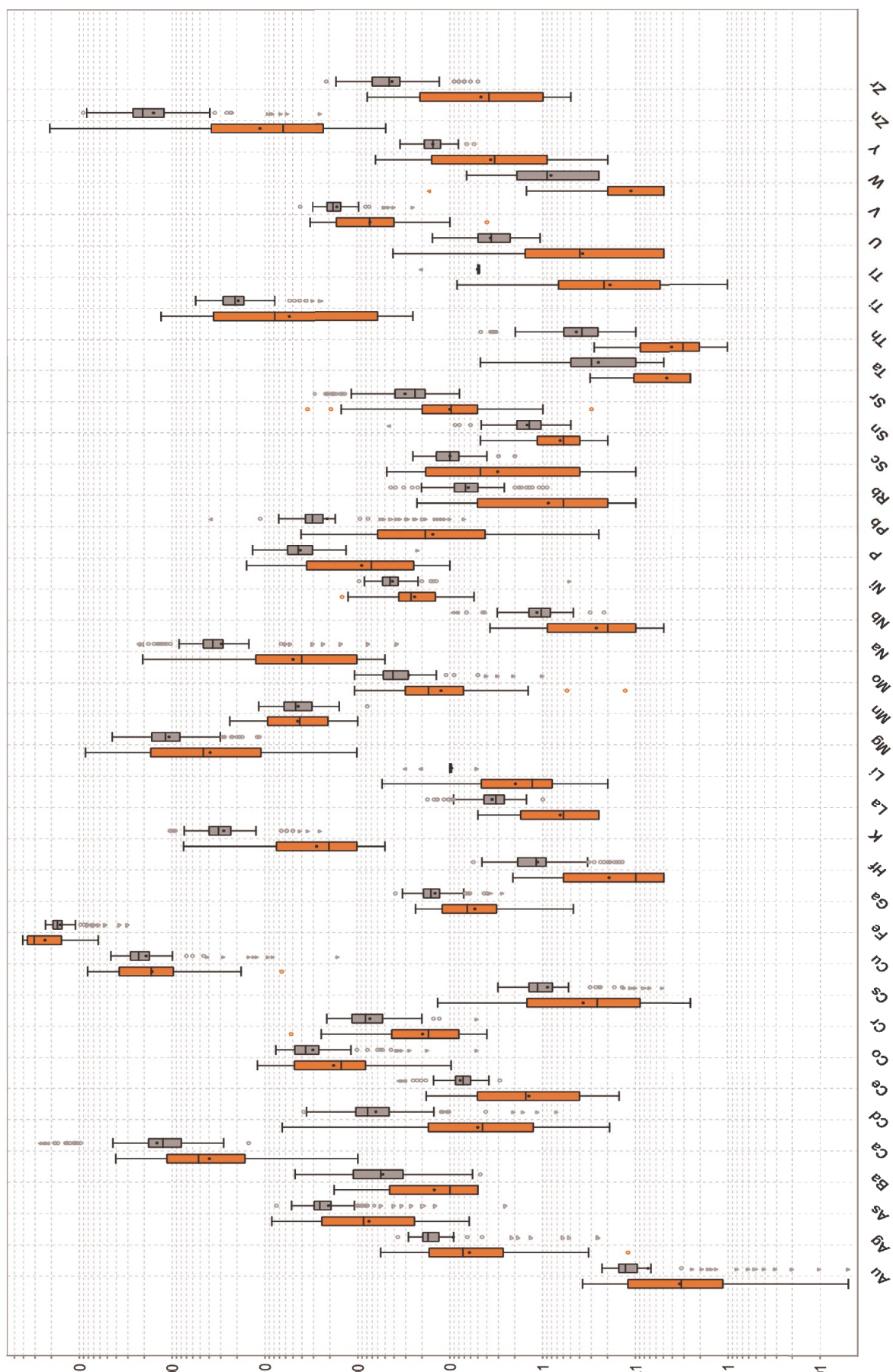


Figure 3.9. Boxplots presenting ore element concentrations (mg/kg) for tailings (grey) and local massive ore (red).

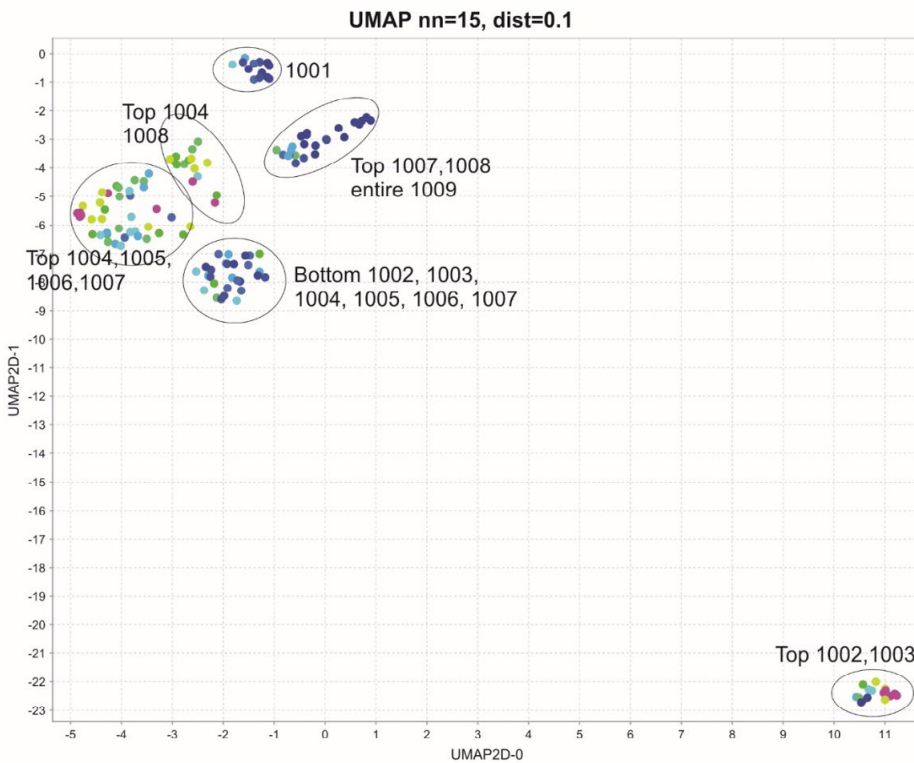


Figure 3.10. UMAP plot that combines all geochemical data from the tailings. The colour of the dots reflects the copper concentrations of the samples (ten categories), the red colour indicating the 90th percentile and darkest blue the 10th percentile.

3.3.5.2 Geophysics

Inversion results for both ERT profiles demonstrate a noticeably clear response to conductive material, with a thickness of up to 10 metres (Figures 3.11, 3.12). The landfill materials are mapped with resistivities between 5 and 15 Ωm , which are shown in the results with blue colours. These areas can without a doubt be linked to sulphides. The transition between the landfill materials and the rock is estimated to be flat, but the resolution is not ideal for being able to either place the bottom of these materials in their exact location or map detailed variations in resistivity within this top layer. It is therefore proposed that the ERT measurements should be repeated with electrode spacing that is less than the 5 metres used in the initial phase of the study. In this way, the resolution will be increased and further details of the internal distribution of resistivities in the tailings will be revealed. Additionally, coverage of the area with several parallel profiles can activate 3D inversion, which will lead to a 3D model of the tailings landfill in Løkken.

The GPR data were plotted in 2D, but since the GPR signal was absorbed by the conductive material in the surface and no reflector was recorded deeper than a few metres, the GPR results should be interpreted in an alternative way. In this context, Figure 3.12 displays the plots of six horizontal slices for a GPR signal amplitude between 145 and 170 metres above sea level, as well as a map showing the positioning of all the profiles measured and how dense the coverage is. Red colours denote a strong signal while blue colours indicate a lack of signal that may be linked to landfill materials, but not exclusively. By following these blue areas, the lateral dimensions of the landfill materials are delineated as opposed to possibly sand and gravel, which are imprinted in red, framing the tailings. Variations in the blue colour indicate changes in the composition of conductive minerals, in which materials containing conductive minerals are mixed with more resistant sediments. However, GPR does not have the capacity to delimit these materials in depth, which results in these

blue areas continuing further below 10 metres from the surface, where ERT has set the boundary between them and bedrock. Finally, it is necessary to mention that the bedrock will also appear in blue in such a process scheme, which means that these two formations cannot be separated using GPR, unlike ERT.

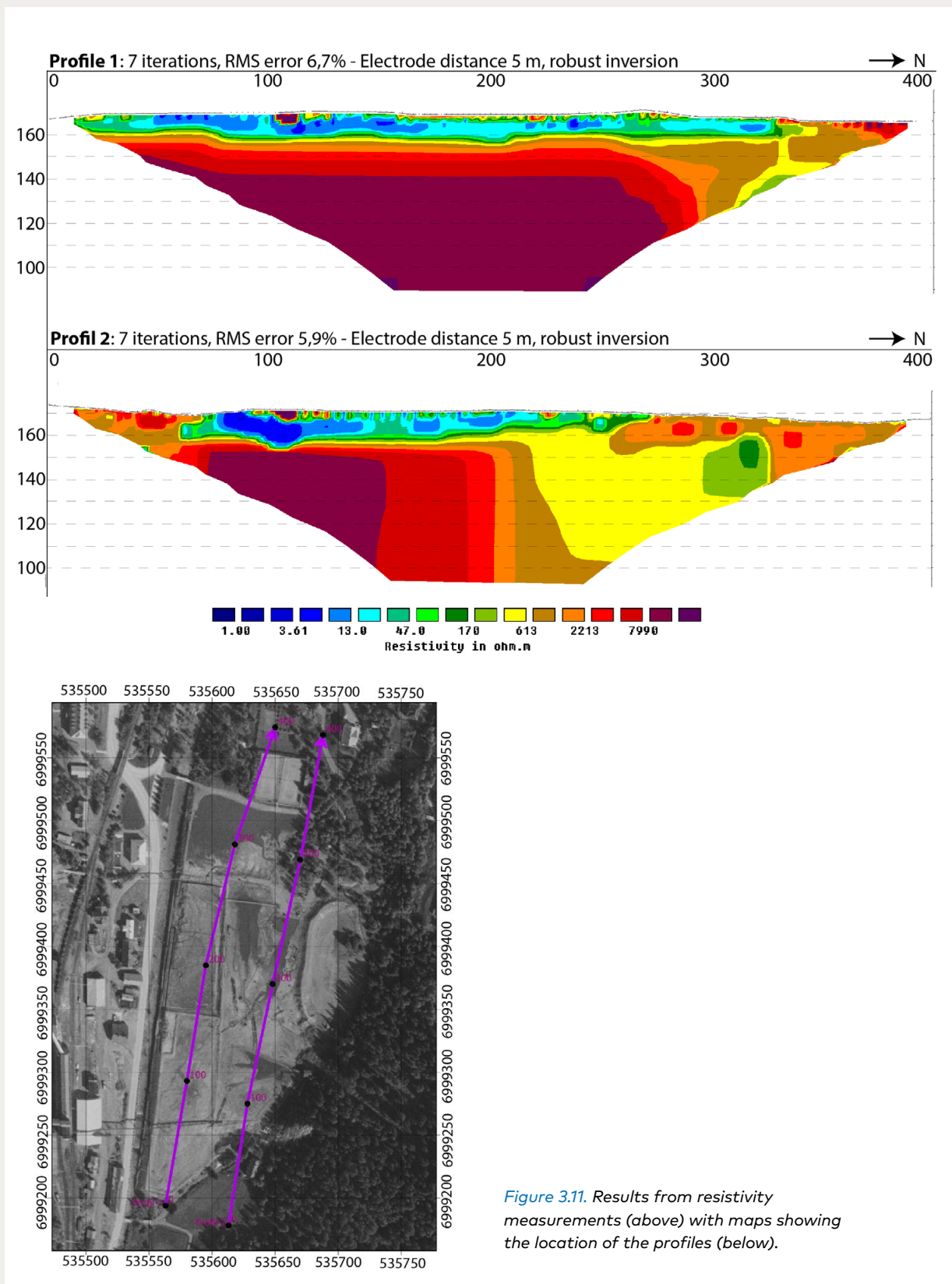


Figure 3.11. Results from resistivity measurements (above) with maps showing the location of the profiles (below).

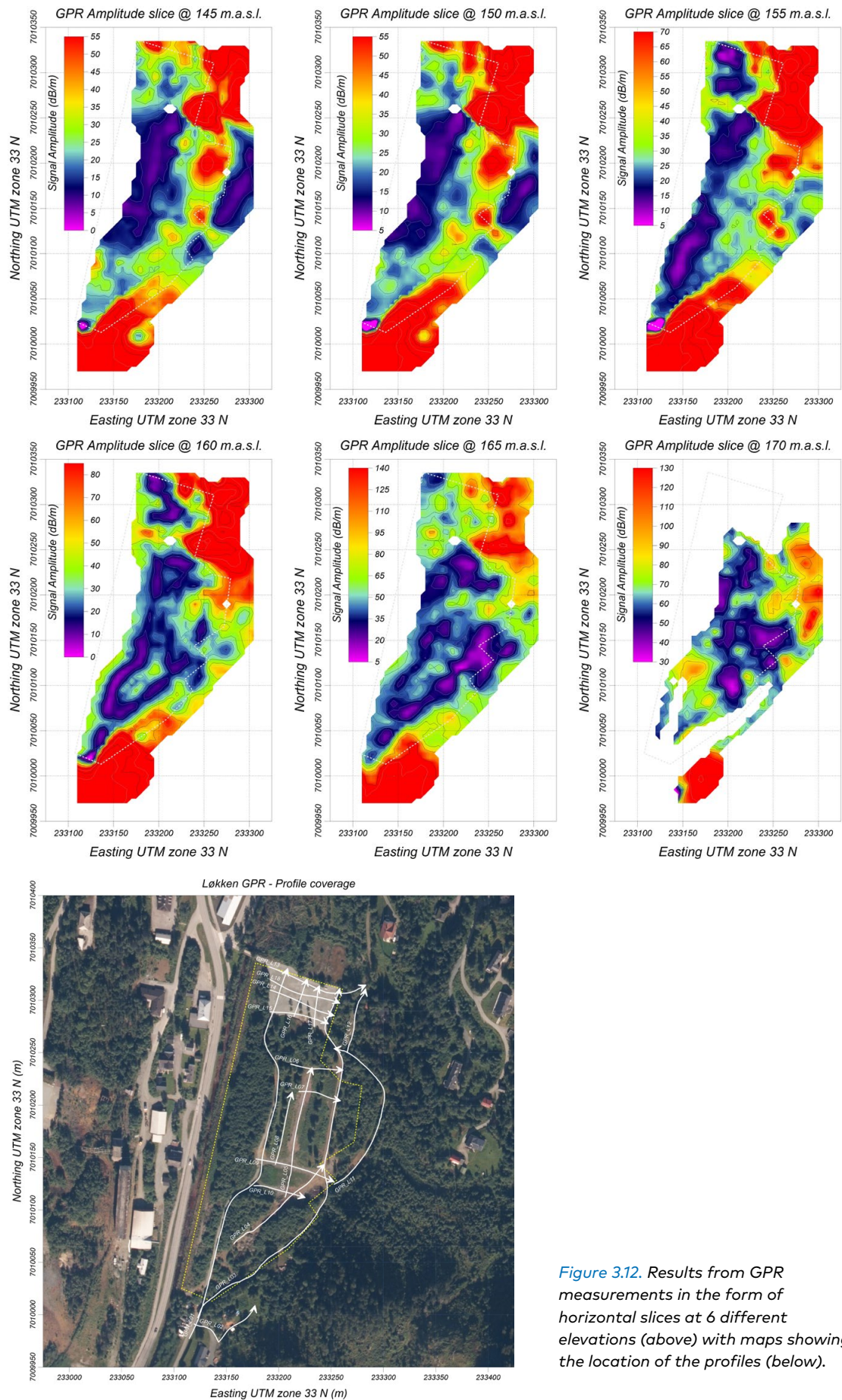


Figure 3.12. Results from GPR measurements in the form of horizontal slices at 6 different elevations (above) with maps showing the location of the profiles (below).

3.3.6 Conclusions from the Løkken study

The Løkken TSF geochemical investigations revealed element concentrations that exceed the concentrations of local massive ore. The similar element composition between primary ore and tailings is not unexpected, as the tailings have not undergone any mineral separation process. The element concentrations vary considerably with depth, and this TSF would therefore show reliable concentration averages only by sampling the tailings deposit from the surface to the bottom. UMAP reveals mineralogical differences in the samples due to deposition time, location and oxidation processes.

The geophysical part of the study revealed that ERT displayed more advantages than GPR when analysing sulphidic tailings. ERT clearly responds to the tailings, but in future studies, the electrode spacing should be reduced to reveal more detailed internal changes within the tailing deposit.

3.4 Building a dataset on mining waste in Norway

For Norway and NGU, this project has been an incentive to learn from previous work on mining waste from SGU and GTK, as well as compile a dataset on potential secondary resources and expand the current knowledge on mining waste as a potential resource, as the mineral resource databases in Norway have primarily covered primary resources.

Unfortunately, closed and abandoned mining sites have not previously been surveyed systematically in national field campaigns. Information on mining wastes, such as volume, composition and the time of deposition, is fragmented, and if documented, represents results from regional surveys or site-specific investigations, or from the monitoring of environmental parameters.

A dataset based on registered waste heaps, covering the location of the primary resource and the estimated volume of waste heaps, was reported to ProSUM in 2017. The dataset originally included 117 metal mining waste sites coarsely estimated to be larger than 1000 m³ and has since been harvested for pan-European databases such as Minerals4EU. As this type of information has not previously been systematically collected, the ProSUM dataset for Norway is incomplete. During this project, the building and expanding of the dataset on mining waste in Norway has included tasks such as:

1. Systematically localising mine waste deposits digitally related to objects in the mineral resource databases, particularly for ore and industrial minerals;
2. Automated volume estimates based on polygons and digital terrain-models;
3. Characterising the mine waste deposits: the waste type (mineral dressing, tailings, cobbing etc.) or dumps, storage conditions and mine waste measurements.

The mapping is not yet complete, but preliminary figures indicate more than 1000 localities with over 2000 polygons, and more than 500 of these polygons have volume estimates of >1000 m³. This is an ongoing task and will

continue after this project has ended. Further work that may be useful for a common Nordic database on potential resources in mining waste will include:

1. Resource assessments and further classifications;
2. Adapting the existing database model and infrastructure to include new data, INSPIRE-compatible parameters and publishing routines for potential secondary resources;
3. Physical examinations and sampling of more localities, in addition to the pilot study at Løkken, including geophysical and geochemical properties and mineralogy.

3.5 Extraction of metals from disposed mining sludge waters

3.5.1 Is there a more sustainable way to treat mine water?

A former copper and sulphur mine in Folldal, Norway, has a problem with acid mine drainage (AMD) from the disposed tailings and from the mine itself. AMD arises when oxygen and water interact with the tailings and ore in the mine. There is a remediation plan to reduce the pollution of the recipient water body, the River Folla (DMF 2022). Each year, 9 tonnes of copper, 6 tonnes of zinc and 130 tonnes of iron drain into the river (NGI 2020) (see Figure 3.13). Several actions are needed to stop the pollution of the river. The largest action in the remediation plan is a water treatment plant that neutralises the AMD by adding an alkali in order to precipitate the metals. The mixture of the precipitated metals and alkali will result in a sludge that is planned to be dewatered and disposed in a landfill (see Figure 3.14). Is there a more sustainable way to treat the mine water, and can one extract the metals rather than disposing of them?

The main objective of this case study within the NSM research project has been to test whether it is possible to extract the metals from the sludge or directly from the AMD to avoid having a large landfill. DMF's project partner has been



Figure 3.13. AMD from the Folldal mine draining into the River Folla. Photo: DMF.

the Department of Chemical Engineering at the Norwegian University of Science and Technology (NTNU). The work plan for the case study consisted of (1) familiarisation with the existing characterisation of the AMD, followed by (2) testing the type of alkali suitable for precipitating the metals and (3) testing the extraction of metals. The results from the case study are reported in the following section and represent a summary of the three project reports by Associate Professor Sulalit Bandyopadhyay and his team.

3.5.2 Promising results in extracting metals at the lab scale

The main objective of this case study has been to test whether it is possible to extract the metals from the sludge or directly from the AMD to avoid having a large landfill.

In part 1, characterisation, gallium was detected in the AMD. However, it was found in such small amounts that it is unprofitable and not interesting to extract. The metals that could be of interest to extract are iron, zinc, copper, nickel and aluminium. The proposed alkalis for precipitation after the characterisation of the AMD were calcium hydroxide (lime) and sodium hydroxide (lye/caustic soda).

In part 2, neutralisation of the AMD was tested with these two alkalis. The use of calcium hydroxide yielded the best settling rates and the best filtration performance (dewatering). This alkali also removed sulphate, which is positive if removal is required with respect to the water quality in the river. The use of sodium hydroxide did not remove sulphate but yielded higher solubility than calcium hydroxide. The amounts of metals that were precipitated did not differ significantly between calcium hydroxide and sodium hydroxide. The conclusion was that calcium hydroxide is the preferred alkali for precipitating the metals in the case study. However, when making the project decisions for the remediation plan in the River Folldal, non-chemistry factors such as cost, HSE (health, safety, environment) and supply security also need to be considered.

For part 3, the initial plan was to investigate the extraction of metals from the sludge or the filter cake (sludge after dewatering). The NTNU research team found this to be a very demanding way to extract the metals, because in principle, the acidic metalliferous water first needs to be neutralised with the alkali to create a filter cake for disposal in a landfill. Then, this process needs to be reversed by using acid to dissolve the filter cake back into an acidic solution with metals. This initial route proved to be demanding and with a highly



Figure 3.14. Sludge before and after dewatering in a Folldal lab test. Photo: DMF.

negative cost–benefit ratio. Therefore, it was decided to investigate an alternative and simpler route whereby the metals are extracted directly from the AMD. The focus of the case study therefore shifted to recovery tests for metals from the AMD water. The methods used were precipitation, ion exchange and solvent extraction (see Figure 3.15).

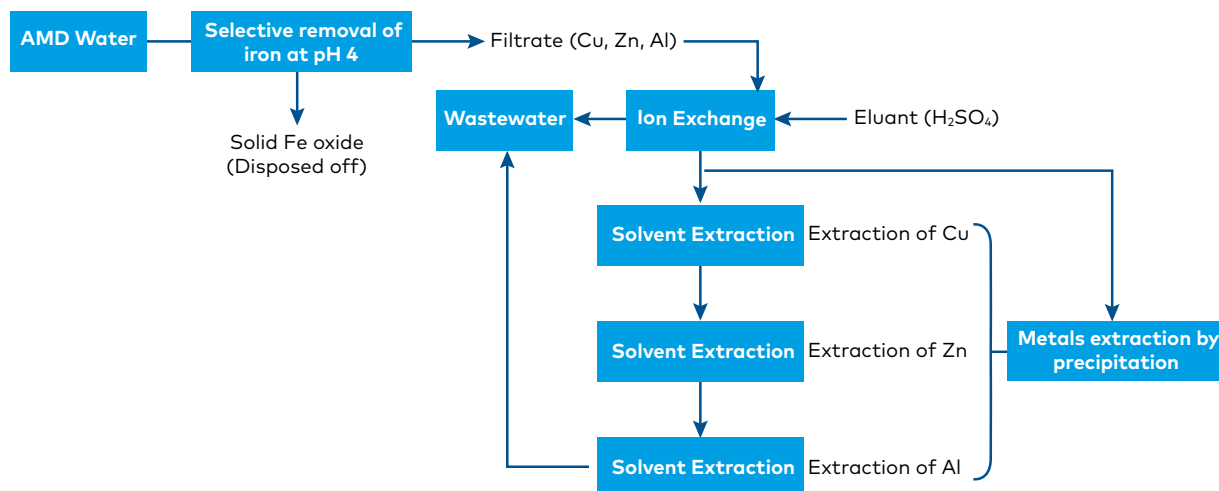


Figure 3.15. Process flow diagram for metal precipitation and recovery (NTNU).

In the first step, iron was removed from the AMD water by increasing the pH from 2.5 to 4. In the next step, other metals in the filtrate were concentrated using ion exchange and eluted by sulphuric acid (see Figure 3.16). Then, the metals in the eluate were separated using solvent extraction. Copper was successfully separated from zinc and aluminium at pH 4 using a cationic chelating extractant, while zinc was not successfully separated from aluminium. Nickel, cobalt and chromium are also present in the AMD, but the concentrations at this point were too low to investigate further.

In addition to solvent extraction, precipitation was tested to recover metals from the eluate. Copper, zinc and aluminium were co-precipitated as hydroxides at pH 7.

The NTNU research team recommends further testing of other extractants to separate zinc and aluminium, and to optimise the ion exchange process for the recovery phase. Further recommended work includes the exploration of

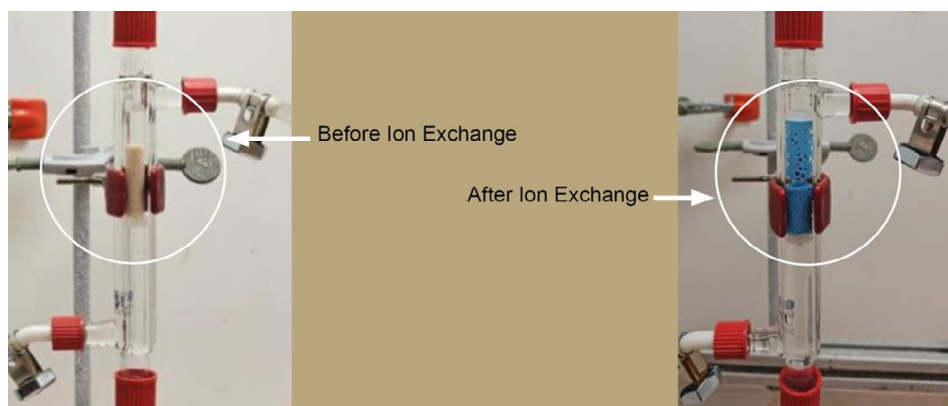


Figure 3.16. Resin bed before and after ion exchange (NTNU).

business cases for the various products made, economic analysis, cooperation with industry and optimising of the recovery steps in the lab before possible pilot-scale tests.

3.5.3 Pollution today – resource tomorrow?

The short-term aim for the remediation plan in Folldal is to improve the water quality in the River Folla in order to meet the demands from environmental authorities (see Figure 3.17). The long-term aim for DMF is to facilitate the development of more sustainable solutions regarding the mining industry. This case study has demonstrated that it is in fact possible to extract metals from the mine water using methods such as precipitation, ion exchange and solvent extraction. It has helped the Folldal project to a better understanding of the challenges in extracting metals from AMD and from sludge from AMD treatment.

From a business-economic perspective, it is not currently profitable to extract the metals using these methods. The promising lab results need to be matured and tested at the pilot scale and in business cases for full-scale extraction. It is therefore recommended to continue the work on investigating different extraction methods and to examine whether any of the possible products can be of interest to European markets, such as the copper and zinc industry.

Extraction of metals is very interesting from a socio-economic perspective. AMD is a common problem related to the mining of copper and other sulphide ores. There is a need to find more sustainable ways to treat mine water, and it would be of considerable interest for society and the environment to be able to use the annually produced 9 tonnes of copper, 6 tonnes of zinc and 130 tonnes of iron as a resource.



Figure 3.17. Tailings from the former copper and sulphur mine in Folldal – waste or resource? Photo: DMF.

3.6 Examination of aluminium dross from the Norðurál aluminium smelter at Grundartangi, SW Iceland

3.6.1 Introduction

The aluminium industry is an important economic player in the Icelandic economy. Operators of the three smelters in Iceland are continuously working to improve the methodology employed at their plants. A highly specialised workforce and service industry has developed around these plants. The operators are also looking for downstream opportunities for their products (Bloxsome 2017). As part of the Nordic Sustainable Minerals initiative, this study aimed to explore the potential of aluminium dross from aluminium smelters in Iceland as a source of gallium or other CRMs.

3.6.2 Background

The most energy-intensive step in the production of aluminium metal is the electrolysis of alumina (Al_2O_3 , or aluminium oxide) to obtain aluminium metal. Aluminium dross is a by-product that forms when molten aluminium reacts with ambient oxygen in the smelting process. There are different types of dross depending, among other factors, on whether the source material is primary or secondary (Manfredi et al. 1997, Meshram & Singh 2018). The basis for this study was simply the idea that valuable metals such as gallium and/or germanium might follow aluminium through the pre-processing of the mined material (bauxite) through to alumina, to the final step of electrolysis to liberate the metal. Furthermore, gallium or other valuable CRM metals might be enriched, relative to the metal, in the dross material.

3.6.3 Methodology

The Al dross obtained from Norðurál was cemented in probe mounts, which are one inch in diameter. The aluminium dross is relatively soft (low hardness) and proved to be difficult to polish. By using wet 4000P sandpaper, it was possible to obtain a suitably polished surface on the mounts. The probe mounts were covered with a carbon coating that serves as a conductive layer to prevent the build-up of charge in the surface of the material under investigation. The probe mounts were examined in a Hitachi TM3000 desktop scanning electron microscope (SEM) at the University of Iceland's geoscience laboratories.

3.6.4 Results

The aluminium dross displays a texture similar to quenched mafic rocks such as sub-marine or sub-aqueous basalts and perhaps reminiscent of komatiites with a spinifex texture. Imaging of the specimen revealed narrow (<4 microns) and highly elongated (>100 microns) laths or needles surrounded by more irregular, almost "globular" material (Fig. 3.18). The apparent texture may to some extent reflect the difficulties with polishing the aluminium dross.

The overwhelming mass of the aluminium dross is composed of Al and O in some proportion. The backscatter images display an even reflectance, with only very minor deviations (Fig. 3.18). There are occasional grains of lower reflectance that appear to be a form of Al–Si–O alloy (Fig. 3.19) and similarly rare high reflectance grains that appear to be Al–Fe–O alloys (Fig. 3.20). The low reflectance grains are larger, ~2 microns, compared to the high reflectance grains, 1 micron.

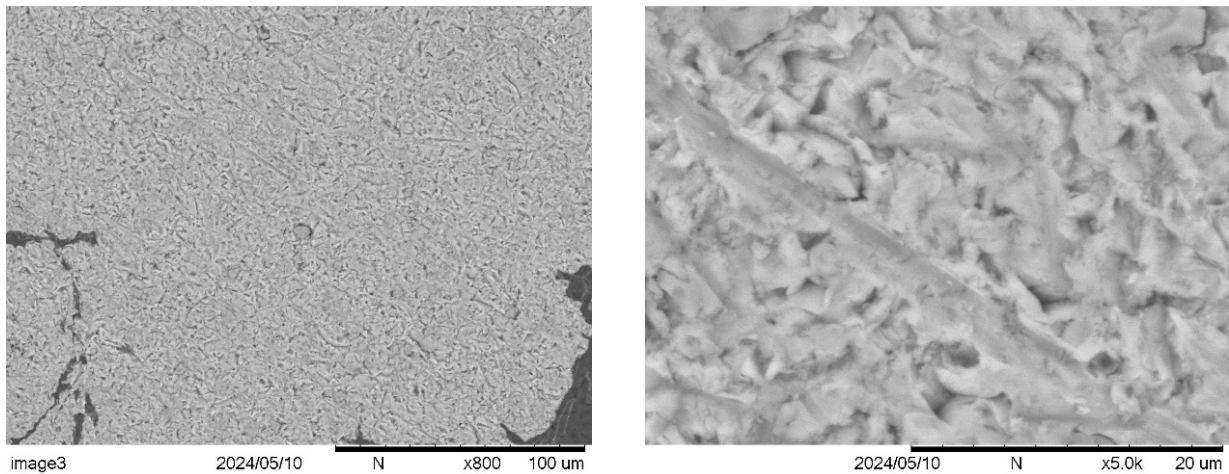


Figure 3.18. Scanning electron microscopy results: (a) 800x magnification of Al-dross from smelter showing "globular" texture and sporadic laths (needles) up to 100 microns in length; (b) 5kx of aluminium-dross showing typical texture of the material including a lath-shaped "crystal";

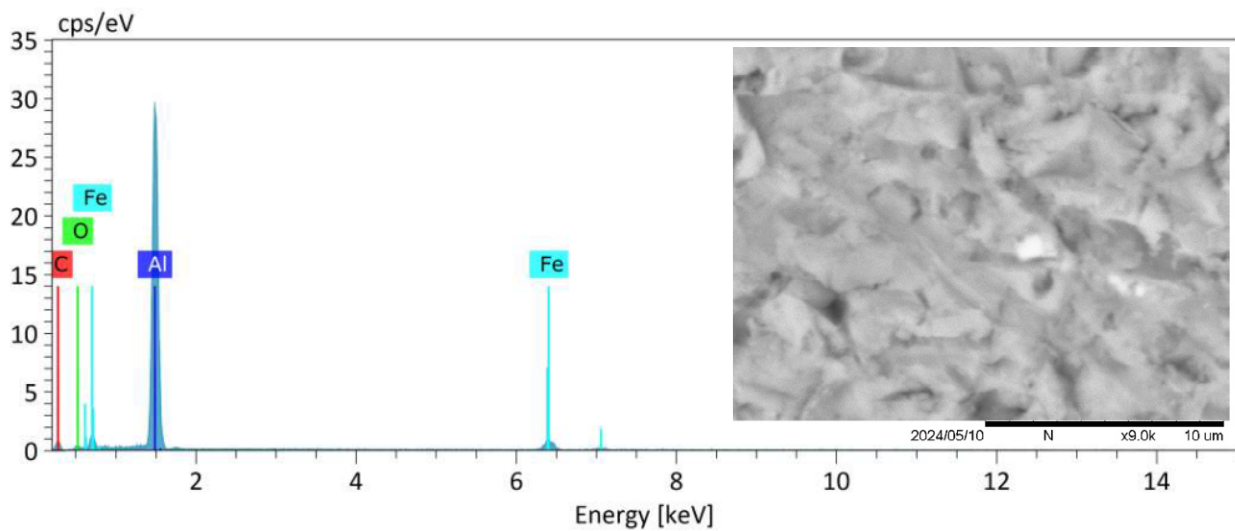


Figure 3.19. SEM image (9k magnification) and spectra of a high-reflectance grain (~ 1 micron in diameter) in the aluminium-dross sample.

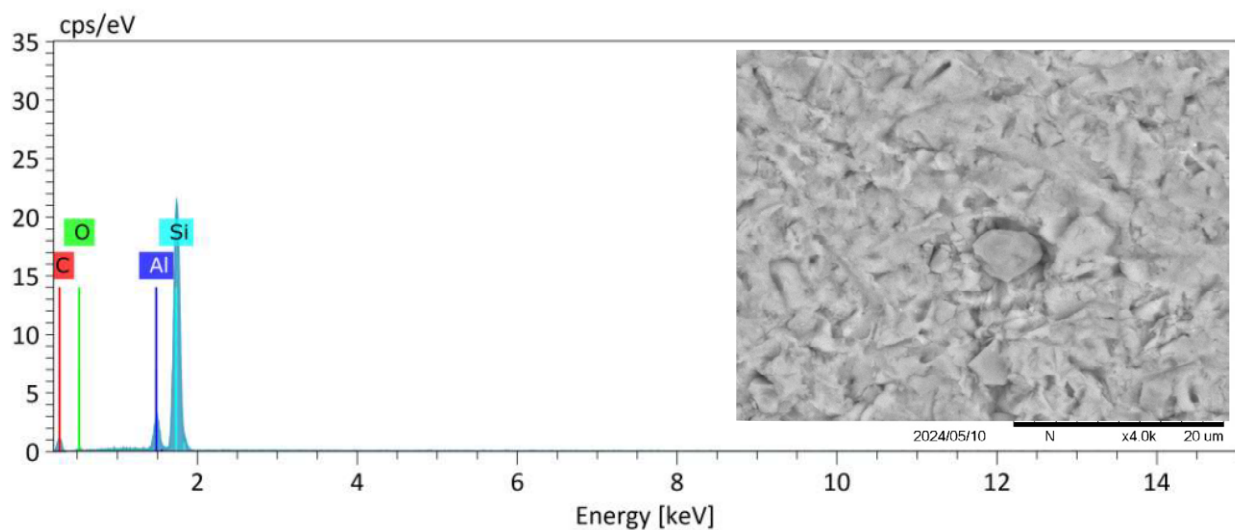


Figure 3.20. SEM image (4k magnification) and spectra of a low-reflectance grain (~5 microns in diameter) in the Aluminium-dross sample.

An attempt to establish the presence of trace amounts of Gallium, that might justify doing further analytical work (e.g. in the electron microprobe), data was collected continuously for 2 hrs from one of the probe mounts. The resulting energy spectra was then examined for Gallium and/or any other metal in the sample. However, nothing beyond background values was observed (Fig. 21). Therefore, we conclude that at the resolution of this analytical method, we did not find any indication of Gallium or other metals in the aluminium-dross that would warrant further investigation.

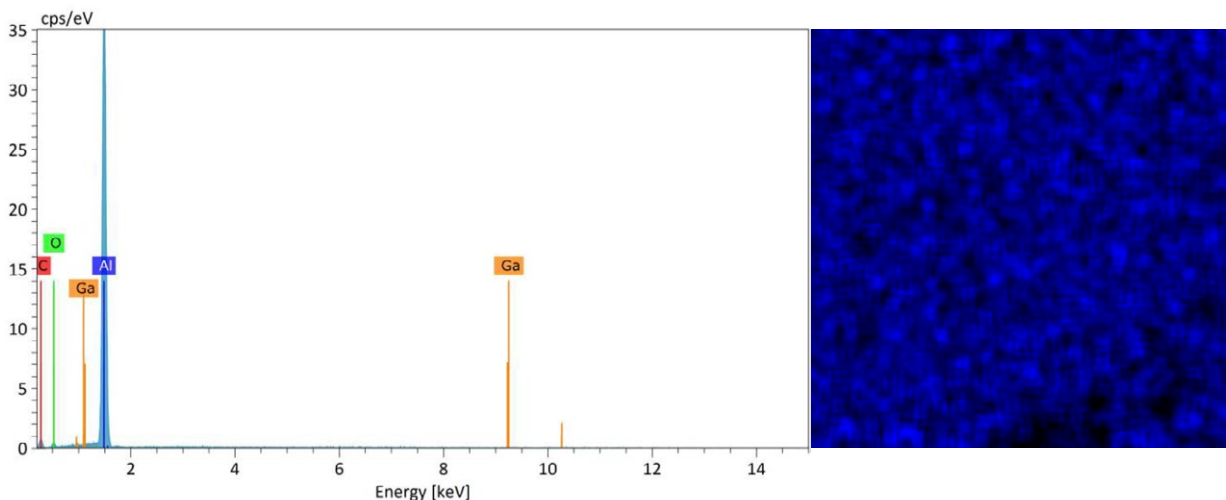


Figure 3.21. Gallium backscatter image (500x magnification; acceleration voltage 15 kV) obtained by collecting for 2 hrs on the aluminium-dross sample (scale bar is 100 μm).

3.6.5 Summary

Samples of aluminium dross from the Norðurál aluminium smelter at Grundartangi were obtained. Probe mounts of the dross were prepared and examined under a scanning electron microscope (SEM). The material appears to be predominantly composed of Al–O alloy with sporadic minute grains of Al–Si–O and Al–Fe–O alloys. No evidence of gallium or other valuable metals was found in the samples.

3.7 CRM recovery potential of fly ash (FA) from Denmark

Waste-to-energy (WtE) power plants in Denmark, also known as municipal solid waste incineration (MSWI) facilities, play a crucial role in the country's waste management and energy production. These facilities convert waste into electricity and heat through combustion processes, which helps reduce the amount of waste sent to landfills and contributes to the overall energy supply.

In Scandinavia, the annual production of fly ash (FA), including flue gas cleaning residues (FGCr) from MSWI facilities, is approximately 54,000 t/yr in Norway, 124,000 t/yr in Denmark, 303,000 t/yr in Sweden, 769 t/yr in Iceland and 750 t/yr in the Faroe Islands (Nordic Council of Ministers 2022). In Greenland, annual production of 900 t/yr has been reported (Kirkelund et al. 2016). The annual volume of MSWI FA produced in Europe is around 2 million tonnes (World Waste Management 2023), with a potential to double if incineration substitutes landfilling (Fig. 3.22).

MSWI FA contains elevated concentrations of many different metals, including EU-critical metals. The heavy and critical metals make up around 5–10%, with the highest concentrations being for the following elements in descending order: Zn, Ti, Sb, Sn, Pb and Cu. Fortunately, efforts are being made at the pilot scale and full scale in Europe, including in Scandinavia, to extract metals and find use for the remaining salts and inert material. Some of the progressing technologies are ASH2SALT, FLUWA/FLUREC, HALOSEP, ARCFUME and NOAH's R&D (IEA 2020).

However, although metal concentrations are elevated within FA, an economically viable extraction process has yet to be demonstrated. Hence, most FA from around Europe, including Scandinavia, is landfilled or stabilised at facilities such as the NOAH facility on the island of Langøya in Norway. Here, waste of differing pH is mixed for stabilization before being deposited in the former limestone quarry. More research and development is needed before this substantial resource can be exploited effectively and economically.



Stalactitic encrustations at the Løkken deposit. Photo: NGU.

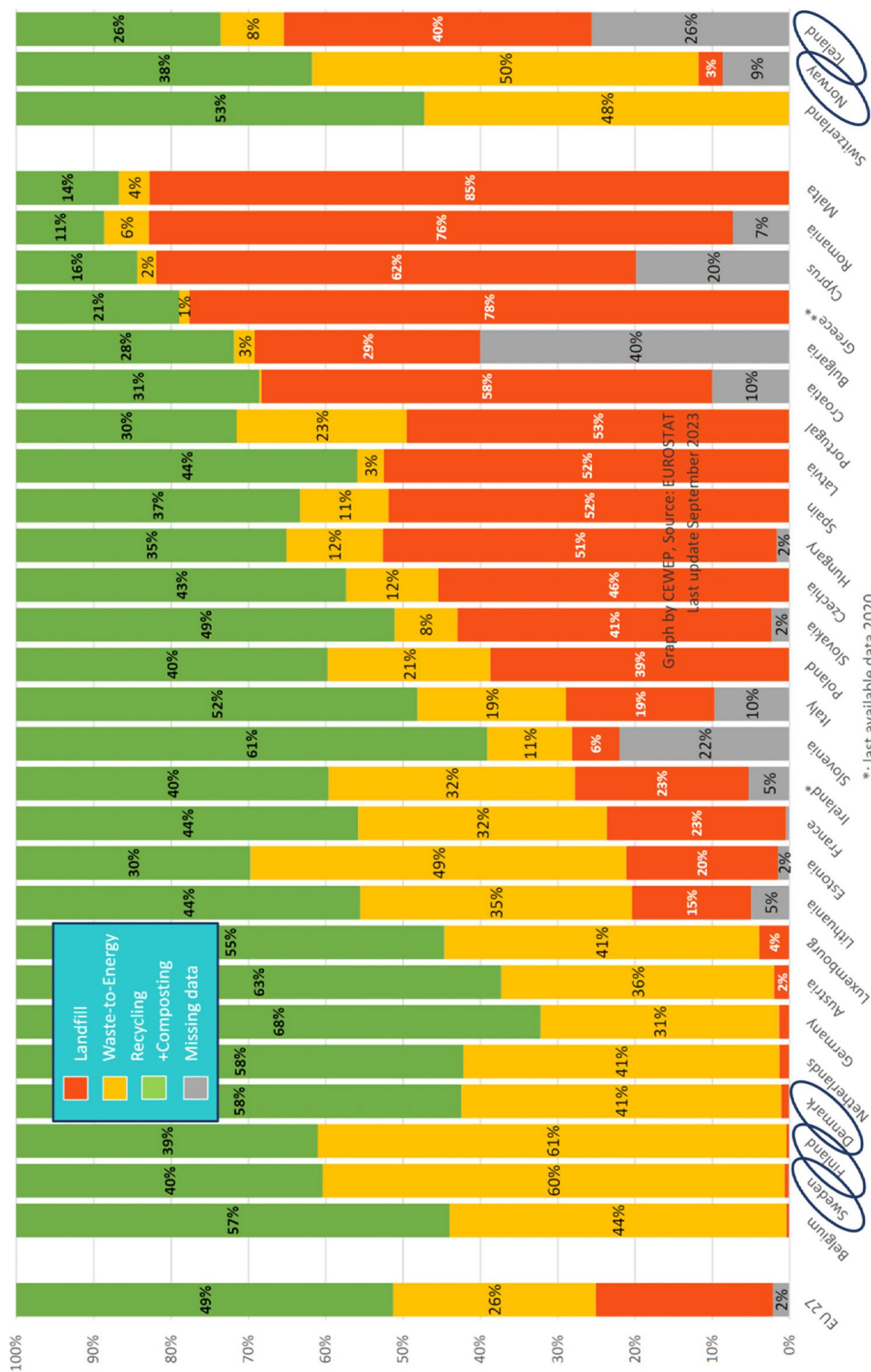


Figure 3.22. Municipal waste treatment in 2021. "Percentages are calculated based on the municipal waste reported as generated in the country". Edit: Nordic countries are encircled. Source: CEWEP 2023.

3.7.1 Purpose of the case studies

In this case study, FA was sampled and geochemically analysed from two different MSWI facilities in Denmark. The purpose of the study was to:

- 1) add a Danish contribution to the Nordic Secondary Critical Raw Material Database (NSCRMD), which will be useful to all Nordic countries and research and development efforts to convert FA waste into a resource in the future;
- 2) test the thesis proposed by Clausen et al. (2019a, b) that FA from waste-to-energy powerplants forms distinct groups of FA inside the powerplant that have a greater resource potential separately than when combined as a single FA material.

3.7.2 Municipal solid waste incineration (MSWI)

Municipal solid waste incinerator (MSWI) facilities represent an advanced approach to managing municipal solid waste (MSW) by converting it into usable energy. These facilities utilise incineration processes to combust waste materials, producing heat which is then harnessed to generate electricity and provide district heating. The incineration process occurs at temperatures between 850 and 1450 °C, with combustion taking place in both the gas and solid phases, simultaneously releasing heat energy. The process generates ashes as a by-product, specifically bottom ash (BA), boiler ash and filter ash, each with unique characteristics and management needs.

There are 28 MSWI facilities in Denmark (Energistyrelsen 2022) producing about 20% of all district heating and supplying 5% of electricity consumption in Denmark (DAKOFA 2024a, b). The powerplants can be divided into three groups (Fig. 3.23) based on input:

- Dedicated MSWI facilities that primarily incinerate household waste and commercial waste, and where at least 80% stems from waste (19 facilities);
- Multi-feed MSWI facilities that incinerate both household waste and commercial waste plus biomass and/or natural gas (4 facilities);
- Special MSWI facilities that only use household waste as co-incineration feed stock or primarily incinerate hazardous waste (3 facilities) (Energistyrelsen 2022).

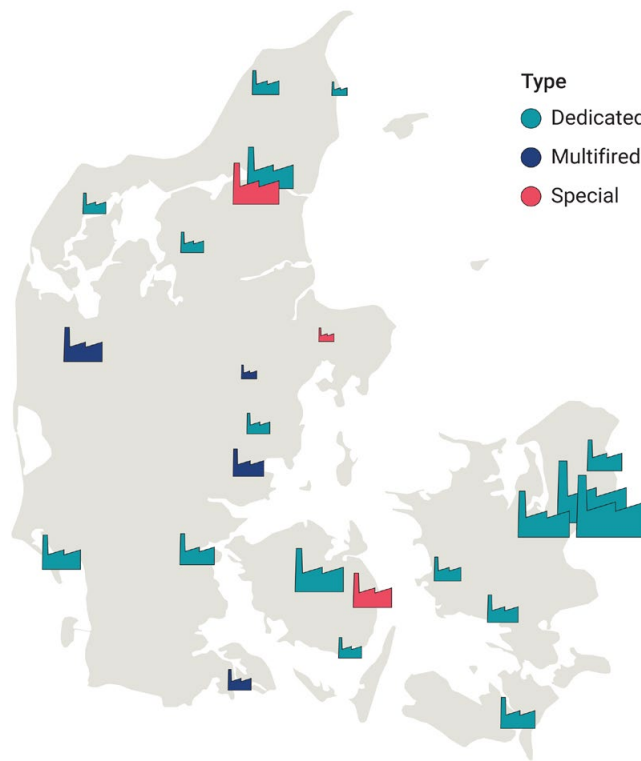
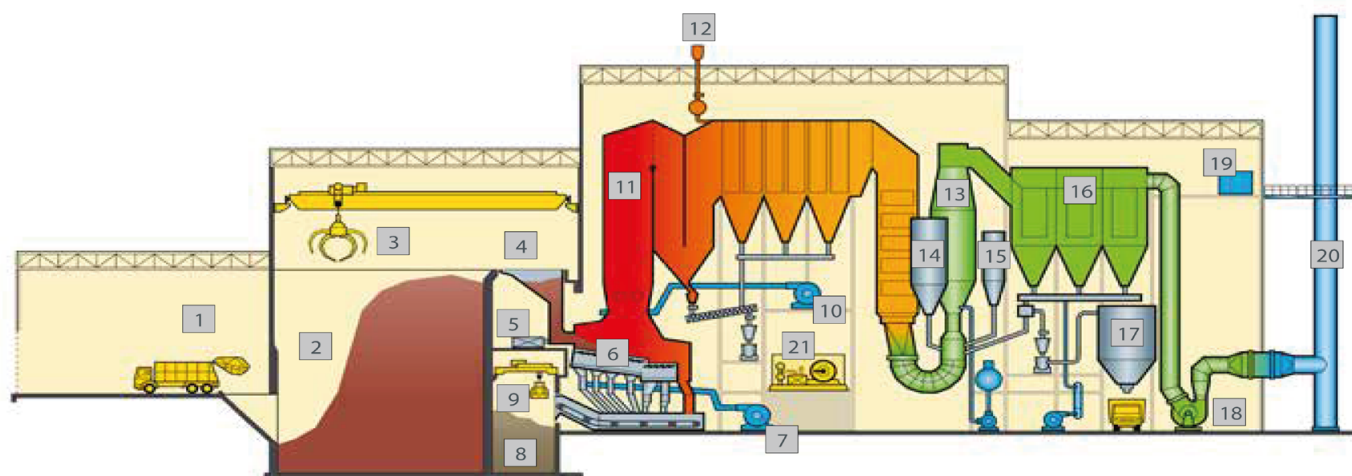


Figure 3.23. MSWI facilities scaled relatively according to size and coloured by type (Energistyrelsen 2022).

Figure 3.24 presents a schematic diagram of a typical municipal solid waste incineration (MSWI) plant, highlighting its main technical components. During incineration, exhaust gases are produced and subsequently cleaned before being released into the atmosphere through a flue (pipe or channel). These flue gases contain most of the available fuel energy in the form of heat, along with dust and gaseous air pollutants that must be removed through a flue-gas purification process. The excess heat from combustion can be utilised to produce steam for electricity generation, district heating/cooling, or steam supply for nearby industrial processes. Plants employing the cogeneration of thermal power (heating and cooling) alongside electricity generation can achieve optimal efficiencies of up to 80%, whereas those generating only electricity reach maximum efficiencies of about 20%.

In the initial stage of gas cleaning, FA is captured by bag filters or electrostatic precipitators. An electrostatic precipitator works by inducing a strong electric field that charges the dust particles (negative/positive charges) combined with leading the flue gas past negative/positive electrode plates. This causes the particles to adsorb to the plates. The particles are then periodically removed by hammering/vibrating the plates and allowing the particles to settle at the bottom. Bag filters are fibrous filters that trap dust in a similar fashion to how vacuum cleaning traps dust in a bag.



WASTE DELIVERY	INCINERATION	FLUE GAS CLEANING	ENERGY RECOVERY
1 Tipping hall	5 Ram feeder	13 Flue gas reactor	21 Steam turbine / generator
2 Waste bunker	6 Incineration grate	14 Hydrated lime	
3 Waste crane	7 Primary air fan	15 Activated carbon	
4 Waste feeding chute	8 Bottom ash bunker	16 Bag filter	
	9 Bottom ash crane	17 Residue silo (fly ash)	
	10 Secondary air fan	18 ID fan	
	11 Steam boiler	19 Emissions Monitoring System (CEMS)	
	12 Boiler safety valve	20 Stack	

Figure 3.24. Schematic overview of an MSWI plant with flue gas cleaning, illustrating the various components of the facility. Image source: GIZ 2017 after Doosan Lentjes GmbH.

Fly ash (FA) makes up about 1–5% by weight of the initial waste input (Belevi & Moench 2000, Chang & Wey 2006, Youcai 2017, Neuwahl et al. 2019) and is finer in texture compared to bottom ash, which makes up about 16–35% of the initial waste input (Seniunaite & Vasarevicius 2017, Silva et al. 2019). The particles carried by the flue gas through the heat recovery units primarily consist of amorphous phases such as silicate glass, oxides and chlorides. Volatile heavy metals, due to their low boiling points, become highly concentrated in FA. These metals either condense on the ash particle surfaces or form new, non-volatile compounds during the cooling process as they travel from the combustion chamber to the flue gas treatment unit. Particles may also agglomerate due to the surface stickiness of condensed compounds on particle surfaces.

As illustrated in Figure 3.25, highly volatile elements tend to concentrate in fly ash (FA), whereas less volatile elements accumulate in bottom ash (Youcai 2017). The concentration of metals such as Zn, Cu, Cd, Pb and Sn in flue gas treatment residues increases with rising furnace temperatures, depending on the melting and boiling points of the respective metal compounds (Belevi & Moench 2000, Youcai 2017). A reduced oxygen supply during incineration results in higher levels of Sn and As in FA while reducing the levels of Zn, Cu, Mo and Sb. However, the oxidation conditions have little effect on the distribution of Cd and Pb (Belevi & Moench 2000). Additionally, the chlorine content in

the waste significantly influences the distribution of metals such as Zn, Cu, Cd, Pb, Sn, Mo, Sb and As: higher chlorine levels promote the accumulation of these metals in FA (Belevi & Moench 2000).

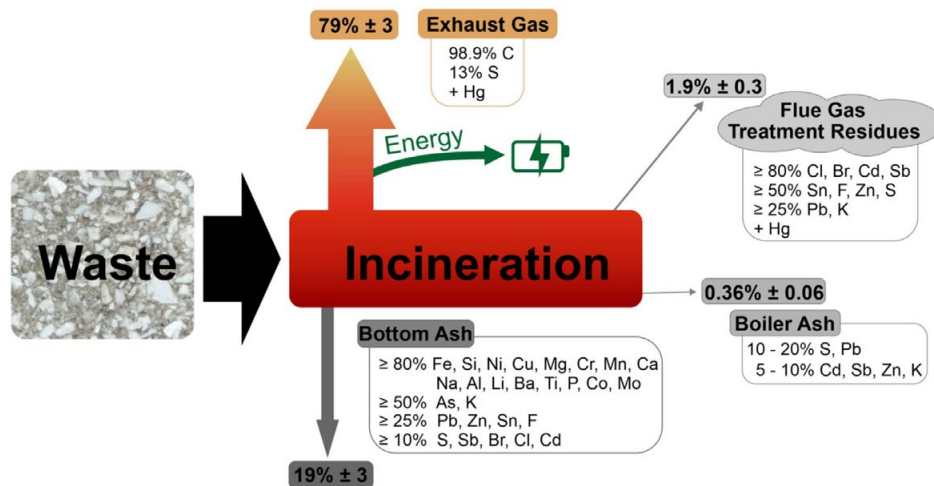


Figure 3.25. The distribution and mass transfer of various elements in exhaust gas, flue gas treatment residues, boiler deposits and bottom ash post-incineration, measured in weight percent (wt%), are depicted in the figure. Source: (Tandon 2021).

3.7.3 The two case studies and reference study

In this project, FA samples were collected and analysed from two of the largest MSWI facilities in Denmark. These results were then compared with a study by Clausen et al. (2019b) on FA from another major MSWI facility in Denmark. Combined, the three MSWI facilities account for about 20% of the annual production of MSWI FA in Denmark. The two MSWI facilities in the case study were the facility in Lisbjerg owned by Kredsløb and the facility in Roskilde owned by ARGO. The reference study focused on the MSWI facility in Copenhagen owned by ARC (see Fig. 3.26).

Apart from their difference in feed quantity and output in terms of heat, electricity and waste residues (Table 3.11), there are differences in the dimensioning and ash cleaning technologies of the three MSWI facilities. For example, ARGO uses bag filters, whereas Kredsløb and ARGO use both bag filters and electrostatic precipitators.



Figure 3.26. The geographical location of the three studied power plants in Denmark.

There is also a difference in whether active coal and/or chalk is injected as part of the flue gas cleaning process, as well as differences in the waste composition, as explained further in the next section.

Table 3.11. Key annual figures for the two case studies (ARGO and Kredslob) and the reference study (ARC). The selected reference year was as close to the year of sampling as possible (ARGO and Kredslob were sampled in Nov. 2023, ARC was sampled Oct.–Nov. 2017).

ARGO in Roskilde		Kredslob in Lisbjerg		ARC in Copenhagen	
Input	2022	Input	2023	Input	2017
MSW, ton	348.204	MSW, ton	216.488	MSW, ton	357.000
Output		Output		Output	
Heat, MWh	1.022,616	Heat, MWh	548.664	Heat, MWh	796.000
Electricity, MWh		Electricity, MWh	107.426	Electricity, MWh	104.000
Bottom ash, ton	-	Bottom ash, ton	36.060	Bottom ash, ton	90.000
FA, ton	-	FA etc., ton	7.139	FA, ton	8.000
CO ₂ , ton	-	CO ₂ , ton	199.000	CO ₂ , ton	-



Photo: Jens Dresling



Photo: Kredslob



Photo: ARC

3.7.4 Waste composition

During the sampling period, the MSWI facilities received three main categories of waste: a) local MSW, b) imported MSW and c) commercial waste. As illustrated in Figures 3.27, 3.28 and 3.29, there are significant differences among the power plants. The composition of MSW varies significantly between municipalities and neighbourhoods, influenced by collection methods, recycling options, citizen commitment to sorting and demographics (e.g., age, family status, mobility). The hand sorting characterization of MSW at ARC provides an indication of the waste composition: 19.9% paper and cardboard, 19% wood, 13.2% plastic, 32.1% food and garden waste, 11.7% glass and building materials, 1.7% ferrometal, 0.8% aluminium and 0.3% WEEE (ARC 2017). Due to the silo capacity and mixing, the reported information on received waste compositions does not exactly match the composition of waste incinerated, but it offers a good indication.

MSWI facilities in Denmark monitor various elements in the flue gas outlet. They analyse carbon isotopes to determine the origin of the emitted carbon dioxide, distinguishing between fossil and biogenic (terrestrial) sources. This analysis provides deeper insights into the composition of the waste being incinerated. The distribution of fossil and biogenic CO₂ during the sampling periods is presented in Table 3.12.

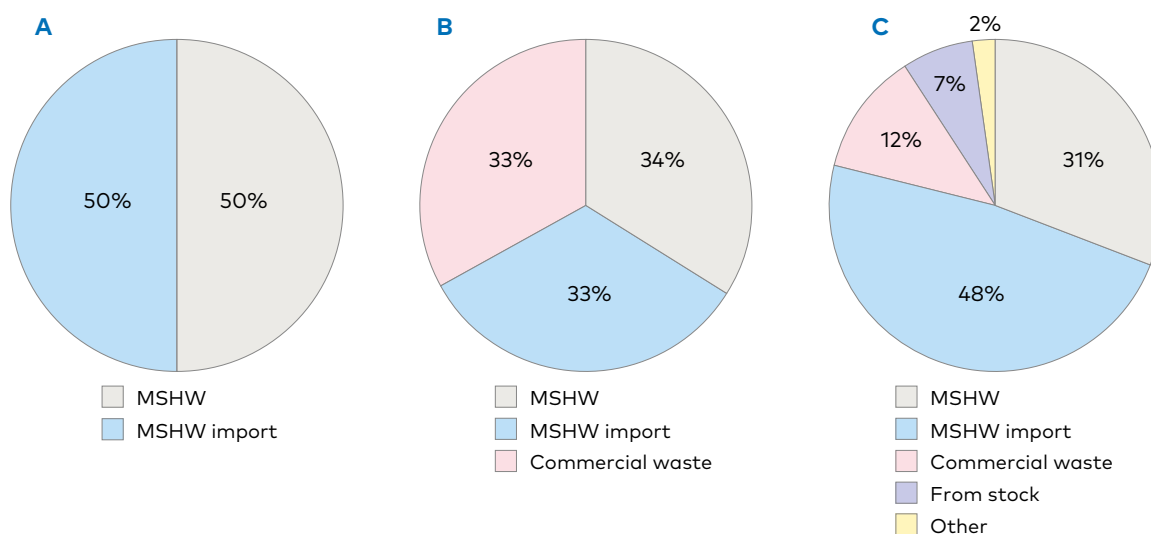
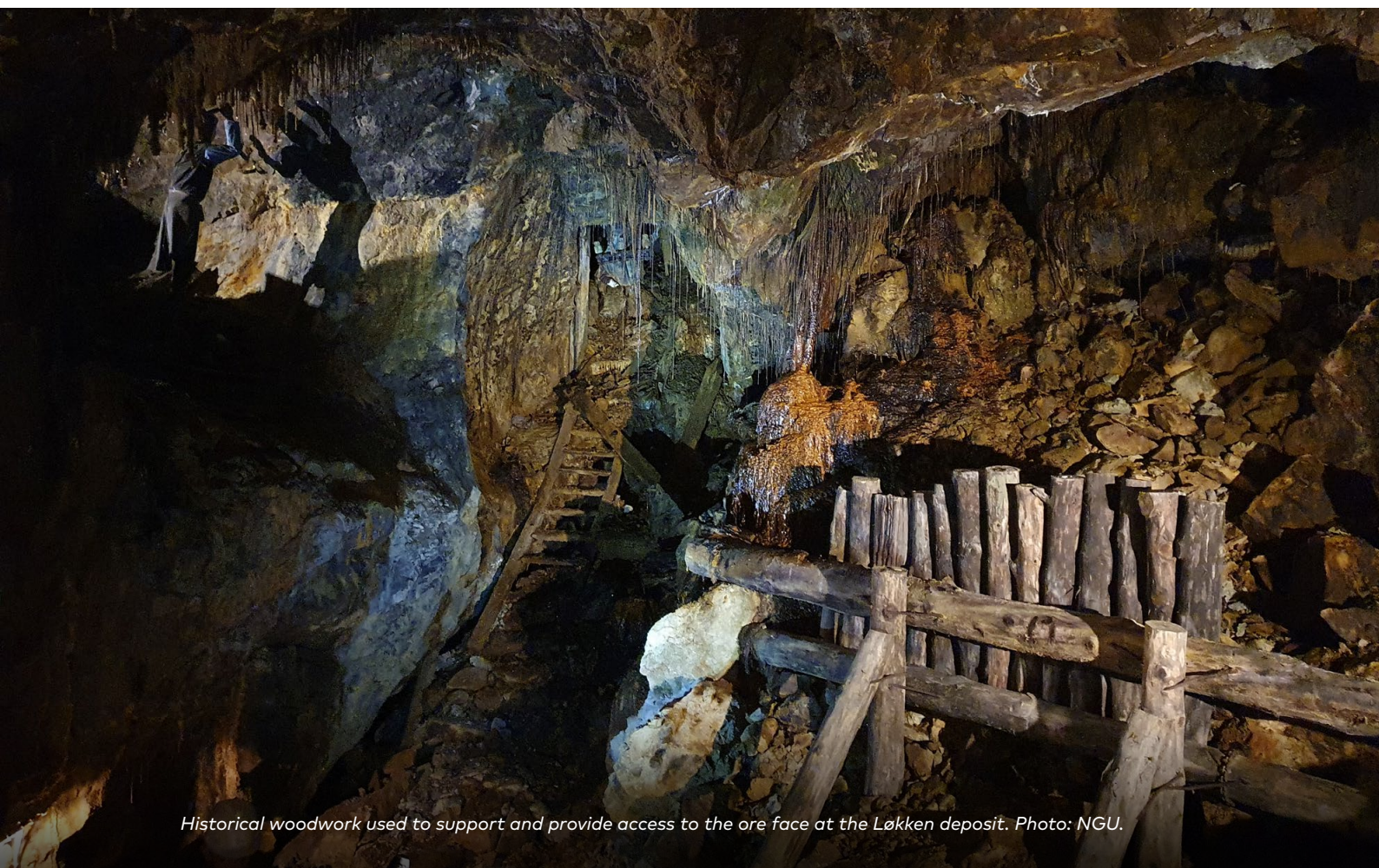


Figure 3.27. Indicative waste composition at ARGO (A), Kredslob (B) and ARC (C) during the respective sampling periods (Nov. 2023 for ARGO and Kredslob, Oct–Nov 2017 for ARC).

Table 3.12. On the basis of C-14 analysis of the flue gas CO₂ in the sampling period at ARGO, Kredslob and ARC, the power plants have provided information on the origin of the carbon, i.e., from fossil or biogenic sources.

	ARGO		Kredslob		ARC	
	Fossil CO ₂	Biogenic CO ₂	Fossil CO ₂	Biogenic CO ₂	Fossil CO ₂	Biogenic CO ₂
Total wt%	42%	58%	51%	49%	-	-



Historical woodwork used to support and provide access to the ore face at the Løkken deposit. Photo: NGU.

3.7.5 Sampling

Altogether, 120 samples of FA were collected from ARGO's MSWI facility over the course of 15 days in November 2023 from eight different sampling spots. In addition, 30 samples were collected from two sampling spots at the Kredsløb MSWI facility, also during the course of two weeks in November 2023. In comparison, the reference MSWI facility was sampled daily for 30 days during November 2017 (Clausen et al. 2019b).

At both facilities, as well as at the ARC MSWI facility, sampling was conducted using a metal cylinder (Fig. 3.28). This cylinder was inserted horizontally into a sampling hole, where it captured the falling FA beneath one of the FA-settling sections (Fig. 3.29). The sampled volume was approximately 0.5–1 litres per sample, and the sampling process took between 1 and 15 minutes per sample.

A



B



Figure 3.28. Typical sampling hole (A) and sampling rod (B). Photo: Kredsløb.

A



B



Figure 3.29. Sampling hole and sampling rod at ARGO's MSWI facility (A). A view of several FA precipitation stages connected to a conveyor belt line on the bottom (B). All stages were sampled during the project. Photos: ARGO.

3.7.6 Geochemical analysis

Composite samples were prepared from the day-to-day samples by splitting and combining sub-samples. Due to the observation of size heterogeneity, the composite samples underwent sieving at 2 mm. This produced 16 composite samples from ARGO (8 samples of <2 mm, 8 samples of >2 mm) and 3 composite samples from Kredsløb (2 samples of <2 mm, 1 sample of >2 mm). The 19 composite samples were then split to approximately 50 grams each, milled and then split into smaller samples ready for analysis, as shown in Figure 3.30.

Analytes were extracted using a spatula after mixing to produce two sample series for analysis: One sample series was leached with HF and analysed for major elements by ICP-OES on an Avio 500 instrument, while trace elements were analysed by ICP-MS on a NexION 1000 instrument. The second sample series was melted with borate and leached with HNO₃ before being analysed for silicium on the ICP-OES Avio 500 instrument. Reference materials were prepared and analysed together with the samples. The following references were used: DISKO-1, BHVO-2 and BCR-2 for major and trace elements (including Si) and OU-6, OShBo and GONV-1 for silicium. The results indicated very little deviance from the reference material values (accuracy close to 99% for all elements).

In order to compare boiler ash and filter ash across the three MSWI facilities, analytical results were weighted together. For ARGO, this meant that analysis results for FA flow 1–7 (boiler ash) were weighed together, and for both plants it meant that analysis results for size fractions were weighed together, thus producing the concentration of boiler ash and filter ash without distinction of the size fraction. The weighted analysis results for boiler ash and filter ash are presented in Tables 3.13, 3.14, and Figures 3.31, 3.32.

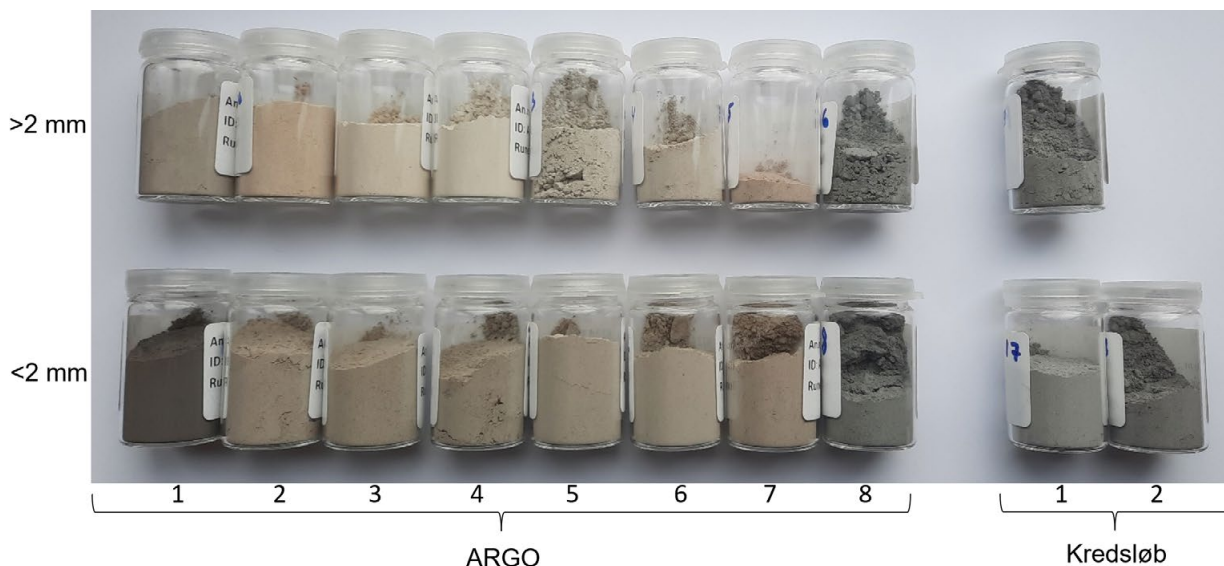


Figure 3.30. The 16 milled samples from ARGO (left side) and the three samples from Kredsløb (right side). Samples are arranged from left to right according to deposition at the plants (8 sampling sites at ARGO, 2 at Kredsløb), with the top row of samples being >2 mm and bottom row being <2 mm samples. Photo: GEUS.

3.7.7 Boiler ash and filter ash – quantitative estimation

Direct measurement of the produced quantities of sub-stream FA does not occur at the MSWI facilities. However, an attempt has been made by the respective operators at ARGO and Kredsløb to estimate the FA distribution between boiler ash and filter ash. The theoretical distribution of sub-stream FA at ARC was estimated by Clausen et al. (2019b) based on the elemental variations and correlations. Table 3.13 summarises the distribution between boiler ash and filter ash for the three MSWI facilities, quantified in terms of annual production.

Further estimations were necessary for ARGO, as eight sub-streams were sampled. The estimated production from each sub-stream is displayed in Table 3.14. Due to the sieving of samples before analysis, the analysis results must be weighted according to the sample weight in the sieved fractions, and these are also displayed in Table 3.14.

Table 3.13. FA distribution between boiler and filter at ARGO and Kredsløb as estimated by ARGO and Kredsløb. The ARC FA distribution was estimated by Clausen et al. (2019b).

	ARGO		Kredsløb		ARC	
	Boiler ash	Filter ash	Boiler ash	Filter ash	Boiler ash	Filter ash
Total wt%	65	35	10	90	60%	40%
Kt/yr.	3.4	1.8	5.6	0.4	4.8	3.2

Table 3.14. Weight of composite samples and estimated production from sample spots at ARGO and Kredsløb.

ARGO				Kredsløb		
Sample spot	Annual production [t. 2023] (estimate)	Composite samples		Sample spot	Composite samples	
		<2mm (measured) [g]	>2mm (measured) [g]		<2mm (measured) [g]	>2mm (measured) [g]
1	360	1,394	151	1 (Boiler ash)	100%	0
2	405	1,617	520			
3	405	1,842	377			
4	675	1,590	208			
5	360	1,216	109	2 (Filter ash)	1,470	4
6	360	1,049	55			
7	360	1,149	39			
8 (Filter ash)	1,575	740	93			

3.7.8 Results

In total, 19 composite samples from the ARGO and Kredslob MSWI facilities were analysed, and the data have been made available to the Nordic Secondary Critical Raw Material Database. Average concentrations in FA from the boiler and filter were calculated (Table 3.15) and selected major and trace elements were plotted (Figs 3.31 and 3.32) to test the hypothesis of Clausen et al. (2019a, b) regarding element affinity in boiler and filter ash.

The geochemical concentrations in boiler ash and filter ash at ARGO and ARC were found to be very similar, and the concentration plots (Figs 3.31 and 3.32) confirmed what was theorised in the previous study by Clausen et al. (2019a, b) that elemental concentrations in FA show affinity towards either the boiler or filter ash. For Kredslob, the same affinity was observed for Ca, Na, K, Zn, Pb, Cu and Cd, thus confirming the hypotheses for these elements. However, for Kredslob, the concentrations of some elements such as Si, Al and Mg did not display affinity towards the boiler ash as expected. Future investigations should aim at identifying the conditions at the Kredslob MSWI facility that caused these differences. Understanding the factors behind the concentration differences is crucial to gain insights into the drivers affecting the concentrations of elements such as Si, Al and Mg.

The findings underline that FA from MSWI facilities should be considered as a multicommodity resource, e.g., the filter ash has elevated concentrations of CRMs such as gallium and copper and of non-CRM heavy elements such as tin, zinc and lead. Other CRMs such as barium, tantalum, rare earth elements, strontium, platinum, cobalt and titanium are found in elevated concentrations in the boiler ash.

Future work should explore the observed variability in the ARGO and ARC samples, which indicates that there is an even greater element affinity/variation in sub-streams of FA than in the combined products of boiler ash and filter ash, respectively. Evaluating the variations alongside logging parameters from the power plants and general knowledge of the plant construction design may also provide insights into the factors determining how and where particles and gases settle throughout the plant. For instance, the settling point of FA particles depends on air speed, turbulence, height and travel time in each flu-gas plant section, as well as on chemical reactions, adsorption and condensation, which are further determined by elemental concentrations in flu gas and particles in combination with temperature.

The average concentration of elements in FA was calculated, and the resource potential for Denmark and EU was quantified (Table 3.16). It should be noted that the calculated potential does not account for the FA from incineration of currently landfilled waste (see Table 3.11) and excludes volatile metals in the fine ash fraction of BA, which could potentially be redirected into FA through power plant redesign. As an indication of whether the calculated resource quantities are significant, we compared the European FA resource potential with global mine production (Table 3.16). Our findings indicate that extracting Si, Sc, Zn, Ga, Y, Cd, Sn, Sb, Ge and As from all European FA could significantly increase the EU raw material security of these metals.

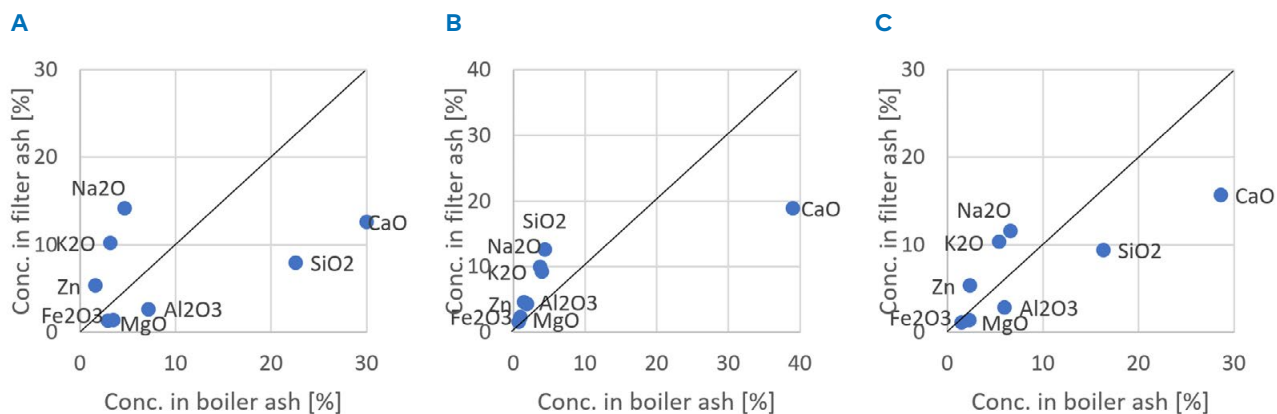


Figure 3.31. Concentrations of selected major elements in boiler ash and filter ash at ARGO (A), Kredslob (B) and ARC (C) plotted against each other.

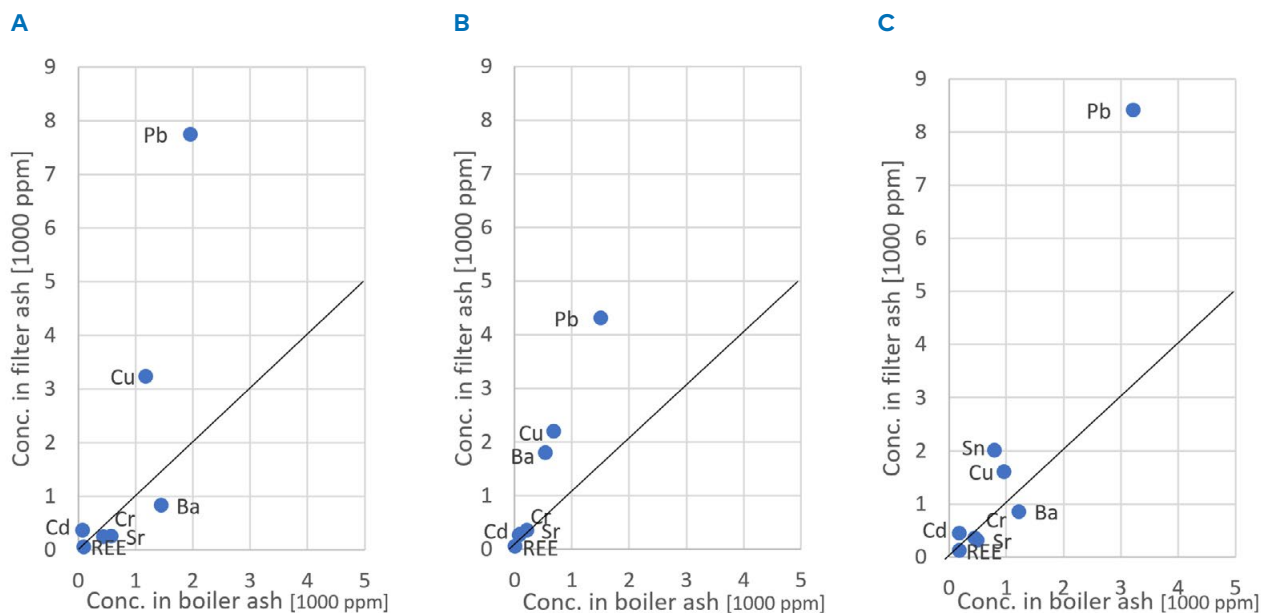


Figure 3.32. Concentrations of selected trace elements in boiler ash and filter ash at ARGO (A), Kredslob (B) and ARC (C) plotted against each other.

Table 3.15. Geochemical composition of boiler ash and filter ash in the three candidate MSWI facilities. Results for ARGO and Kredslob are based on the weighted average of main and trace element analysis from the boiler and filter ash samples. The geochemical composition of boiler ash and filter ash at ARC was estimated by Clausen et al. (2019b).

Element	ARGO		Kredslob		ARC	
	Boiler ash	Filter ash	Boiler ash	Filter ash	Boiler ash	Filter ash
SiO ₂ , wt%	23	7.9	4.4	13	16.3	9.4
•TiO ₂ , wt%	2.1	0.80	0.4	1.4	1.6	0.77
•Al ₂ O ₃ , wt%	7.2	2.7	1.5	4.6	6.0	2.8
Fe ₂ O ₃ , wt%	3.5	1.4	0.8	1.6	1.5	1.1
•MnO, wt%	0.10	0.05	0.0	0.1	0.09	0.07
•MgO, wt%	2.9	1.3	1.0	2.3	2.3	1.4
CaO, wt%	30	13	39	19	28.6	15.7
Na ₂ O, wt%	4.7	14	3.8	10	6.6	11.6
K ₂ O, wt%	3.2	10	4.0	9.2	5.4	10.3
•P ₂ O ₅ , wt%	1.2	0.64	0.3	0.3	1.3	0.88
•Li, ppm	27	56	21	53	27	45
•Sc, ppm	5	13	3.4	12	NA	NA
•V, ppm	52	27	15.4	41	47.6	56.6
Cr, ppm	444	234	89	251	456	350
•Co, ppm	34	16	11	34	14.8	11.2
•Ni, ppm	130	61	35.8	89	48	56
•Cu, ppm	3,234	1,181	691	2,183	964	1,604
Zn, wt%	1.6	5.2	1.9	4.3	2.4	5.3
•Ga, ppm	9.3	14	4.8	10	10.2	18.4
Rb, ppm	63	218	68.1	157	75.6	232
•Sr, ppm	577	250	210	350	506	300
Y, ppm	13	4.9	5.0	7.6	NA	NA
Zr, ppm	137	46	24.3	77	115	63.8
Mo, ppm	15	12	6.3	18	12.6	12.4
Cd, ppm	74	369	104	266	181	445
Cs, ppm	3.2	12.3	3.7	7.8	1.9	7.9
•Ba, ppm	1,452	827	549	1,790	1,231	854
•LREE, ppm	93	57	14	35	179	119
•HREE, ppm	6.3	2.2	1.7	3.3		
•Ta, ppm	1.6	0.5	0.2	0.8	1.1	0.54
Pb, ppm	1,960	7,748	1,515	4,299	3,224	8,405
Th, ppm	3.6	1.3	0.7	1.8	2.5	1.4
U, ppm	1.4	0.6	0.7	0.8	1.1	0.61
Sn, wt%	NA	NA	NA	NA	0.08	0.2
•Sb, wt%	NA	NA	NA	NA	0.1	0.25
•Ge, ppm	NA	NA	NA	NA	1.8	4.8
•As, ppm	NA	NA	NA	NA	227	375
•Bi, ppm	NA	NA	NA	NA	10.7	11.4
•W, ppm	NA	NA	NA	NA	6.0	4.3
•Pd, ppb	NA	NA	NA	NA	17.8	2.2
•Pt, ppb	NA	NA	NA	NA	84.6	58.6

• CRM, NA: Not analysed

Table 3.16. Average geochemical composition of the analysed FA. The weighted average of boiler ash and filter ash concentrations (Table 3.15 weighted with Table 3.13). An indicative estimate of the total annual element quantity in FA produced in Denmark and the EU assuming avg. element concentrations. Data on global mine production were retrieved from USGS Commodity Summaries 2022–2024 (USGS 2024).

Element	FA avg. conc.	Resource potential		
		FA DK [t/yr]	FA EU [t/yr]	FA EU / Global mine production
SiO ₂	16 wt%	19,972	322,133	4%
•TiO ₂	1.6 wt%	1,931	31,140	<0.5%
•Al ₂ O ₃	5.4 wt%	6,700	108,067	<0.5%
Fe ₂ O ₃	2.1 wt%	2,628	42,380	<0.5%
•MnO	0.1 wt%	106	1,707	<0.5%
•MgO	2.3 wt%	2,896	46,713	<0.5%
CaO	25 wt%	30,731	495,667	-
Na ₂ O	7.6 wt%	9,374	151,200	<0.5%
K ₂ O	6.4 wt%	7,953	128,267	<0.5%
•P ₂ O ₅	0.9 wt%	1,080	17,413	<0.5%
•Li	37 ppm	5	74	<0.5%
•Sc	8.1 ppm	1	16	65%
•V	47 ppm	6	94	<0.5%
Cr	364 ppm	45	728	<0.5%
•Co	26 ppm	3	53	<0.5%
•Ni	88 ppm	11	177	<0.5%
•Cu	2,163 ppm	268	4,325	<0.5%
Zn	3.1 wt%	3,812	61,484	1%
•Ga	11 ppm	1.3	22	5%
Rb	116 ppm	14	233	-
•Sr	446 ppm	55	891	<0.5%
Y	10 ppm	1.3	20	1%
Zr	101 ppm	13	202	<0.5%
Mo	15 ppm	1.8	30	<0.5%
Cd	204 ppm	25	407	2%
Cs	5.0 ppm	0.6	10	-
•Ba	1,399 ppm	174	2,799	<0.5%
•LREE	94 ppm	12	187	<0.5%
•HREE	3.1 ppm	0.4	6.3	<0.5%
•Ta	1.1 ppm	0.1	2.2	<0.5%
Pb	3,759 ppm	466	7,518	<0.5%
Th	2.4 ppm	0.3	4.9	<0.5%
U	1.0 ppm	0.1	2.0	<0.5%
Sn	0.1 wt%	159	2,560	1%
•Sb	0.2 wt%	198	3,200	3%
•Ge	3.0 ppm	0.4	6.0	4%
•As	286 ppm	35	572	1%
•Bi	11 ppm	1.4	22	<0.5%
•W	5.3 ppm	0.7	11	<0.5%
•Pd	12 ppb	0.001	0.023	<0.5%
•Pt	74 ppb	0.009	0.148	<0.5%

• CRM

4 The Nordic Database: integration of primary and secondary mineral resource data

Cloud computing has substantially evolved over the last 20 years (Papatheodorou 2014, Zhan 2015, Hu 2017, Nasr 2018, Gupta 2020). The expansion of the availability of services also includes the capability of hosting relational (SQL-capable) databases and their related data management services in the cloud, which has resulted in a simplified approach where non-IT specialists can develop such resources, providing benefits to a much wider community of users. Progressive automation and interoperability are increasing connections to artificial intelligence and machine learning models, allowing more advanced forms of data analysis, visualisation and processing. Serverless computing, such as AWS Lambda (Amazon Web Services 2020a, b), has become more prominent, eliminating the need for extensive back-end server management and allowing, for instance, automatic scaling of applications based on consumer needs. This flexibility is well suited to geoscience database development dedicated to hosting multidisciplinary data requiring experimentation and the automation of processes that allow record search, statistical analysis and data visualisation. All these aspects are vital to the interpretation of geoinformation for decision support.

Creating a database that could provide access to information on primary and secondary resources data is challenging for several reasons. The first problem is the identification of data

to be stored in the system. Another problem is the selection of hardware/software solutions to allow the display and query of the data, as well as its efficient management. Here, we discuss the approach adopted to archive primary and secondary mineral deposit and mining waste data and their classification.



Malachite ore staining on a mineralised ore face at the Løkken deposit. Photo: NGU.

4.1 A cloud-based repository for primary and secondary mineral resources in the Nordic countries

A prototype of the Nordic Database (ND) has been developed, (potentially) providing access to available (identified) primary and secondary mineral resources data via the World-Wide Web (this represents a minimum viable product, MVP; see Fig. 4.1 for a simplified structure of the database configuration). The system is more data inclusive than current Nordic country databases (e.g., the Nordic Ore Deposit Database, NODD, and the Metso Finnish ore deposits database) and allows more efficient data sharing and simplified retrieval of records. The resource is hosted on a private cloud server, the Amazon Web Service cloud, with its physical cores sited in Stockholm.

The database can be accessed through a permanent IP address (reported account credentials in Table 4.1), and it can be used in ArcGIS or QGIS to connect to the geospatial tables and visualise the data. It is possible to evaluate the results of some of the data compilations and classification systems discussed in the report (section 4.2); the same credentials can be used to access the IP directly using the Adminer (Vrána 2024) interface (Table 4.1, list of credentials).

Table 4.1. Guest user account details to connect to the AWS server for data consumption and usage.

NORDIC DATABASE ADMINER ACCESS
The online published server has the following address: http://134.122.65.82/adminer-4.8.1.php
The credentials to access the server are the following: System: PostgreSQL Server: database-nscrm-1.ce2tfuvx6fxt.eu-north-1.rds.amazonaws.com User: guest Password: nordics2024 Database: NORDIC_DBS

Its development was dedicated to the generation of a resource that has research and experimentation as the main purposes to advance understanding of methodological approaches to treat multiscale and multivariate geoscience data in areas that examine the interfacing between mineral deposit studies and computational applications to mineral resources databases (Nassar et al. 2015, 2021, Werner et al. 2015, Jowitt et al. 2018, Mudd et al. 2018).

The system was developed to address some of the current limitations of the NODD relational database, an exhaustive, up-to-date, high-quality compilation of primary resources focused on metallic ores in the Nordic countries (Eilu et al. 2007, Eilu 2012). NODD does not support functionalities to simplify the development of SQL queries on a virtual server to filter and consume specific information publicly (or privately). Furthermore, it does not include data on secondary resources (NSCRMD component of the current ND implementation, Fig. 4.1). Given these limitations, research was conducted to test unconven-

tional approaches to data sharing, providing an experimental workflow for the development of a database that connects primary and secondary resources in a cloud-based environment, by using relational tables in the cloud.

The implementation uses the Adminer database management interface (Vrána 2024) to manage updates and data searches (for multiusers, live, on a web browser), which translated into unexpectedly efficient access to information on mineral resources. A common web browser such as Google Chrome or Mozilla is used to access the resource, which is particularly useful to share information and functionality (e.g., SQL query capabilities) across a multitude of platforms (e.g., iOS, Android, Microsoft Windows, macOS), thus eliminating, although not excluding, the need for complex GIS software or other geospatial mapping solutions such as dedicated web GIS servers. The platform also provides a rapid way to update the information using pgAdmin and/or directly using Adminer, which would significantly reduce the time lost in updating resources of this type, leading to savings (database compilation phases are often a very labour-intensive activity). This database system could also help with legacy data issues, since it allows relatively rapid data migrations and fusion/integration from multiple independent users.

The results obtained at a more detailed level can be summarised according to the area of research considered during prototype development: (1) data compilation, (2) database system and design, and (3) establishing the CRM potential of secondary resources (this is the resource classification stage, addressed in this section using the concept of criticality (section 2.6), and expanded in the economic classification or valuation, discussed in section 4.2). We briefly discuss the work carried out in each area of research and provide a summary of the relevant information pertaining to the results obtained.

4.1.1 Workflows and methodology adopted and database organisation

This subsection discusses the framework and how the data archival system was designed. Experimental work was carried out to develop a fusion or data integration of existing mineral resource data on primary (ore deposit) and secondary (mining waste) resources and upscaling of geochemical information on secondary resources, to obtain an aggregated database on mining waste materials connected to an existing primary resources database, the NODD. Building databases is an iterative task, as the quality and completeness of the information is progressively improved over extended periods, requiring constant updates that were outside the primary research objectives of this project. At present, any decision involving the usage and application of the resources should be considered carefully given such limitations, which also inherits all the limitations that apply to the data migrated from other resources such as the NODD or other downloaded data packages (publicly available). The critical objective of this project was to outline possible avenues for the improvement of workflows for the data acquisition stage and the design and interrogation of data repositories hosting mining waste and potentially other types of waste data.

4.1.1.1 Data compilation

The compilation of a database on mining waste is challenging for several reasons. Some of the aspects to consider are common to other database development projects, data quality and availability being the most critical factors, followed by the time consumed in compiling or updating records. Another more specific problem when dealing with mineral resources data on ore deposits and waste is their legacy. Often, this results in data heterogeneity in both format and data reporting standards. For this reason, several potential sources for the required data were evaluated and, in most cases, used to arrive at a consistent representation of specific records.

The data compilation stage was approached from different angles, initially by considering existing databases and evaluating their compatibility in terms of data fields stored and record duplication rates and secondly by developing software that could handle and partly automate processes that integrate information (Annex A). For instance, the use of relational links that bind primary and secondary resources was particularly useful to migrate contextual information from the NODD table into the NSCRMD table on mining waste data (Fig. 4.1). Several data sources were considered (see references in Table 4.2).

Table 4.2. Summary of the most important data sources considered for the generation of a prototype database of primary and secondary resources (Gaál et al. 2012, Kuusela 2015, Tornivaara et al. 2018, Kinnunen et al. 2022, Jonsson et al. 2023, SGU & Naturvårdsverket 2023).

Id	Dataset	Evaluated records	Country	Content	References / Web link
D01	Tukes Archive Environmental Sites	>50	Finland	Information on environmental permitting for operations in Finland.	https://tukes.fi/
D02	S&P Capital Pro IQ Platform	>200	Nordics	Mineral deposit and production plant data.	platform.spgi.spglobal.com/
D03	ProMine Database	>50	Nordics	Information on CRMs and mining waste.	EGDI/Mintel4EU
D04	ProSUM Database	>100	Nordics	CRMs REFRAM, report containing ProSUM records on CRMs.	EGDI/Mintel4EU
D05	Malmkemi Geochemical Database	>200	Sweden	Geochemical database of Sweden.	www.sgu.se/
D06	NODD (Nordic Ore Deposit Database)	>500	Nordics	Nordic Ore Deposit Database (primary mineral resources data covering the Nordic countries).	https://hakku.gtk.fi/
D07	Study on tailings in Finland	>30	Finland	Historical overview of selected waste sites (TSFs).	Tornivaara et al. (2018)
D08	Zn deposits, geochemical data in Finland	>10	Finland	Research on zinc deposits in Finland with a geochemical database (includes tailings).	Kuusela (2015)

Table 4.2. Cont.

Id	Dataset	Evaluated records	Country	Content	References / Web link
D09	Nordic study on the CRM potential of active and closed mines	>20	Nordics	Several records on primary deposits containing CRMs.	Jonsson et al. (2023)
D10	Selection of case studies based on NI proposal	>5	Nordics	Case studies considered as part of the NSM program WP2 package on recycling and re-mining.	NSM WP2 (prepared in 2022)
D11	Finnish Environment Institute (SKYE)	>20	Finland	Several reports, projects.	www.syke.fi/
D12	Regional Environmental Centres (ELY Centres)	NA	Finland	Several reports, projects.	www.ely-keskus.fi/
D13	Literature search for individual mine sites	NA	Nordics	Several company sites (e.g., Boliden).	www.boliden.com/
D14	Mapping of Innovation-critical Metals and Minerals Report	>200	Sweden	Report on Sweden geochemical data.	Hallberg & Reginiussen (2019)
D15	Nordic Innovation Report on CRMs in the Nordic countries	>100	Nordics	Report on importance of CRMs for the Nordics.	www.nordicinnovation.org/
D16	MINDAT Resource	NA	Global	Global primary mineral resources data.	www.mindat.org/
D17	Mining Industry and Tailings Disposal	>10	Norway	Report with summary of tailings.	www.miljodirektoratet.no/
D18	A Review of Circular Economy Strategies for Mine Tailings	>10	Finland	Geochemical database records.	Kinnunen et al. (2022)
D19	SGU 2023 Geochemical Database	>100	Sweden	Geochemical database records.	SGU & Naturvårdsverket (2023)
D20	Hydrogeochemical Database (Folldal)	>10	Norway	Hydrogeochemical data on AMD waters.	DMF (provided in 2023)
D21	Global Tailings Database	>20	Global	Tailings data on mines and plants.	https://tailing.grida.no/
D22	Malmer	>100	Sweden	Swedish mineral deposit data.	www.sgu.se/en/mineral-resources/geological-information-for-mineral-exploration/
D23	Norway Ore Deposit Data	>50	Norway	Norway mineral deposit data.	https://geo.ngu.no/download/order?lang=en&dataset=500
D24	GTK Geodata and Mineral Deposit Reports	>50	Finland	GTK portal for ore deposit consultation.	https://gtkdata.gtk.fi/mdae/index.html

The adopted data compilation workflow led to the integration of two main databases, one on primary resources derived from the Nordic Ore Deposit Database, NODD (Eilu et al. 2007, 2020, Eilu 2012), and the other entirely new, generated with the aggregation of multiple sources of information as listed in Table 4.2 and termed the Nordic Secondary Critical Raw Material Database (NSCRMD). The concept and original conceptualisation of an integrated system of this type was termed the Pan-Nordic Database (Eilu et al. 2021) or simply the Nordic Database (ND), as referred to in this report. The data compilation derived from the NODD represents primary mineral deposits or prospects with at least some minimal information about their mineral resources (e.g., reported drill intercepts) and is represented by a total of 1,526 records (mid-2023 update).

The compilation of secondary resources (NSCRMD table) includes partial information on the volume and mass of waste data, as well as geochemical information on several waste locations, mostly representing tailings, rock dumps materials and slag. The number of records in the NSCRMD table stands at 582 (Fig. 4.2). Variable levels of data completeness are present, limiting its applicability. Despite these challenges, useful inferences and classification workflow developments were possible, as illustrated in section 4.2.

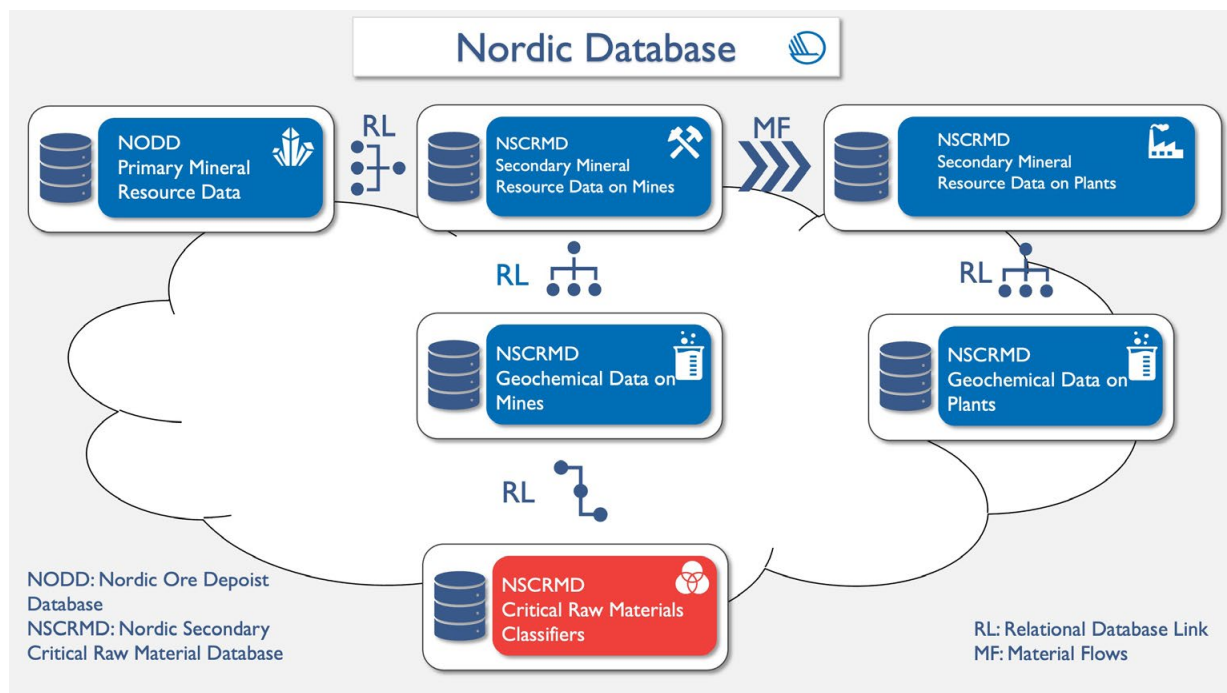


Figure 4.1. Simplified database schema illustrating the data tables and the relative relationships (RL) considered (two types, one-to-one and one-to-many). MF represents a schematic of the material flow and indicates that a transfer of material occurs between mines and plants such as refineries or smelters. The pan-Nordic database considers the following modules: (1) the Nordic Ore Deposit Database, NODD, and (2) the NSCRMD system. Two NSCRMD geochemical databases are also present and allow the retrieval of geochemical information at the sample level. A final database contains a set of classification fields allowing information to be grouped according to the following criteria: (a) the probability of CRM occurrence and (b) strategic importance according to the EU CRM Act (EU Commission 2023a). Economic importance is based on updated commodity prices and market size estimates (McNulty & Jowitt 2021, USGS 2023).

To populate the database, two distinct approaches were devised: (1) the identification of waste sites in available geochemical sampling campaigns or studies on the waste materials (Hallberg & Reginiussen 2019, SGU 2023) and (2) the study of primary resource databases and other compilations, including secondary resources associated with the primary ores, to determine mining waste production data (Eilu et al. 2007, Eilu 2012, Jonsson et al. 2023). These compilation strategies served distinct purposes. The first was to map sites that could be independent of primary mining sites but holding CRM potential, and the second was a gap filling strategy to identify ore deposits that had significant past or present production and were likely to be associated with significant waste that had as yet not been considered in the initial compilation (overburden and mineralisation tailings produced during ore concentration are often proximal to a primary mineral deposit, Fig. 1.4).

4.1.1.2 Database system, design and experimental work

In the simplified representation of the database in Figure 4.1, the basic structuring of the tables and several relational links (RLs) utilised to allow selection query operation and consistent record updates are documented. Primary and foreign keys were used to force specific constraints using complete record IDs, thus ensuring that updates would be compatible with the data table's rules enforced in the database schema (each SQL statement is validated against these constraints when updating or selecting records). Two public schemas were used, *public* offers PostGIS functionality for the conversion of georeferenced data into geospatial layer formats. The second schema was instead used to archive multiple updates of the resources in table form and thus does not support PostGIS functionalities (*public_nsp* schema).

Different cloud computing solutions to host the Postgres instance were considered. The main cloud computing providers are Microsoft Azure (Azure), Google Cloud Platform (GCP) and Amazon Web Services (AWS). The AWS solution was selected among them, because of the unique and vast range of services available in its ecosystem (including support for both raster and vector data, and a range of machine learning tools that could extend the implementation functionality). An additional design feature considered the representation of data tables as geospatial data. Geospatial IDs enabled access to the database resource (together with the installation of PostGIS extensions), allowing GIS software interactions (e.g., ArcGIS and QGIS, Fig. 4.2). Geospatial layers were produced for the NODD and NSCRMD to allow data visualisation in a geographic context.

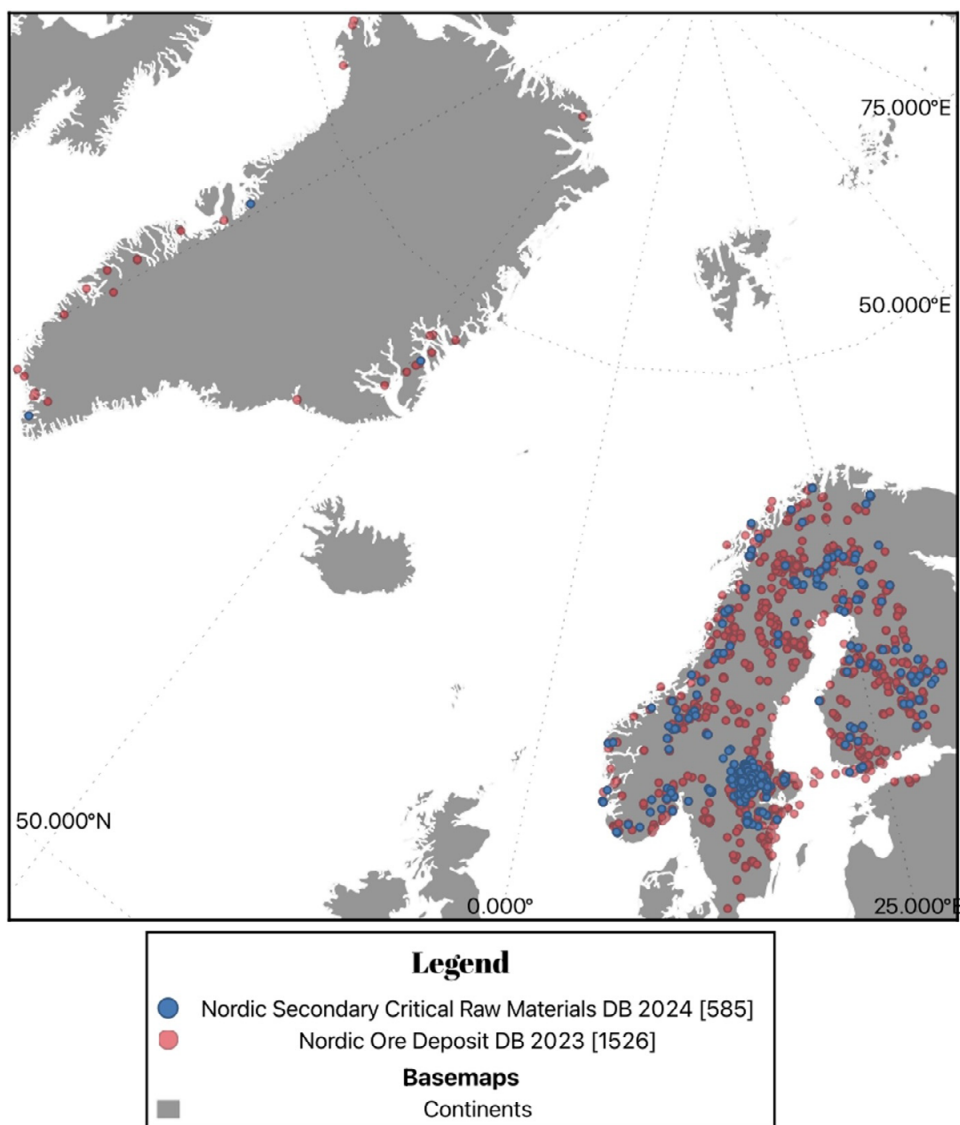


Figure 4.2. Comparison of the coverage of two databases integrated in the ND compilation. Blue dots represent identified sites with CRM potential (n = 585) predominantly representing waste rock material from mining dumps, tailings and concentrates. Red dots represent all the primary resources records considered (n = 1,526). NODD data from Eilu et al. (2007), updated (30-08-2023).

The ND system is a prototype that involved significant and extensive experimentation. The following experiments were carried out to understand how current practices in collecting and investigating tailings and other waste could be integrated and used effectively to locate and characterise potential waste sites enriched in CRMs:

- (1) Geochemical mining waste data aggregation and its representation;
- (2) Probabilistic evaluation of CRM contents in primary ore and mining waste;
- (3) Economic valuation of primary ore and secondary resources, treated in section 4.2;
- (4) Query development to extract information relevant to the identification of mining waste sites associated with primary mineral resources data.

A brief discussion of these experiments and some of the results obtained are provided here to illustrate the benefits of the Postgres implementation. Two Swedish geochemical databases (Hallberg & Reginiussen 2019, 2020, SGU & Naturvårdsverket 2023) were reprocessed to evaluate how to import and map geochemical data, to allow the integration of these records with the coarser scale data available from other compilations that represented averages of mineral resources or waste data (i.e., several publications report waste data as linked to specific deposits, similarly to what is done for primary resources) (Kinnunen & Kasonen 2019). The experimental work considered the evaluation of how this information could be treated and connected to primary resource data on mine sites to better qualify their CRM potential by complementing geochemical results with information derived from the mineral deposit data (e.g., ore genetic style, mineralogy). Mineral resources summaries are commonly averages of many data sampling campaigns (e.g., the entire drilling assays from a primary mineral deposit at a specified cut-off grade), while regional geochemical databases instead report individual sample multielement results). This heterogeneity in scale and level of representation created a challenge in terms of aggregating subpopulations of geochemical data according to their location, analytical methods and representativity to ensure data compatibility. Algorithms and relative scripts were devised (using the R language, see Annex A) to automate the calculations of mean, median, mode and standard deviation of the geochemical data to allow the presentation of geochemical summaries for individual locations represented by multiple geochemical samples. These results were aggregated into the NSCRM database so that the information could be kept separate from the primary mineral resources summaries available in the NODD table and could be connected to both the NODD, where any overlaps existed, and to the original database, e.g., SGU geochemical compilations (Hallberg & Reginiussen 2019, SGU & Naturvårdsverket 2023). These locations refer to mining waste areas instead of primary ore sites where mining activities have occurred, extending the mapping of localities (e.g., waste rock dumps and tailings mainly in Sweden). The application allowed the upscaling of Swedish geochemical data to the same scale of representation as mineral deposit databases presenting averaged mineral resource data, rather than individual geochemical sample data (i.e., average grades of reported metals/minerals).

Another more conventional approach was adopted in a subsequent data gap analysis that involved comparing records presented in the NSCRM with country-specific databases that were processed using a combination of Adminer SQL queries and QGIS analysis and filtering of information to increase data completeness. This work mainly considered Norway and Finland, for instance by using data on mineral deposits from the Finnish ore deposits database (Metso, <https://gtkdata.gtk.fi/mdae/index.html>), which has important information on the waste mass for Finnish deposits.

4.1.1.3 Prediction of CRM potential

A second experiment was developed by constructing a relational link between the NODD and NSCRM tables to allow the joining of fields, ensuring consistency in information exchange across the data tables, with the purpose of migrating information on primary raw materials and to permit the construction of a classification field (an intermediate stage of the CRM potential evaluation, estimated for each primary deposit using the SR and EI scoring reported in 2023 by the EU Commission), which was subsequently transferred

(joined) to the NSCRMD records (the SR_EI score discussed below represents a multiplicative score that combines SR and EI scores for individual deposits and represents the numerical result used for ranking deposits according to their CRM potential). The primary objective was to devise a system that could analyse the current primary resources data in the NODD and based on several rules defining likely CRMs that could be present in a mineral deposit.

A heuristic approach was adopted, developing software (Annex A) that would infer the presence of specific elements given their companionship and by consideration of specific ($n = 42$) ore deposit styles already defined and attributed in the NODD database for the classification of ore deposit records. The addition was developed to improve the accuracy of algorithm prediction by considering expert knowledge on polymetallic associations commonly found in specific ore deposits (Fig. 4.3 provides an example for the Cu case). The ore deposit style was used to constrain the polymetallic associations. For instance, porphyry Cu deposits exhibit specific base metal associations (Cu–Au vs Mo–W with distinct by-product associations), (Herrington 2011).

4.1.1.4 Selection queries for the identification of CRM sites with significant waste materials

The final experiment conducted using systematic SQL structured queries (Table 4.3) was directed at the identification of primary mineral deposits in the NODD table with significant CRM potential and with a cumulative ore production above the 0.15 Mt. This empirical threshold was selected based on the case studies considered in section 3.2 (some of the examples included relatively small tonnages of waste if compared to major operations. This limit reduces the number of deposits to be evaluated, but it does not affect the classification results obtained in Table 4.4). Operations that had a history of mining were assumed to have potential for considerable amounts of waste on-site (provided the limitation that in some instances, mineral concentration facilities may be located at a considerable distance from a source mine). A secondary objective of this experiment was to identify sites that were not catalogued in previous iterations of NSCRMD development. Comparative analysis of the results of SQL filtering with the NSCRMD records allowed further inference and identification of deposits that could be associated or were a source of significant waste materials.

Further analysis was conducted by examining the periods of operation of the mines used to develop subgroups separated by country and mine status (active vs closed; Table 4.4 provides a summary of the top operations sorted by mined material). Mineral deposit records were sorted by cumulative production to emphasise the importance of multiyear operations exploiting large deposits and producing significant waste (for instance, the Kevitsa deposit in Finland is a good example of an actively mined operation with a wealth of information on the production of ore and waste) (see Table 4.4 and SRK Consulting 2020).

In this experimental SQL work, structured queries were developed in Adminer, as summarised in Table 4.3 with a list of the SQL statements and in Figures 4.4 and 4.5, presenting the basic interface of Adminer and an example of how it can be configured to filter the information of interest. The advantage of using Adminer to retrieve records is connected to the simplicity of creating custom SQL queries and consequently performing complex record and field analysis. In this context, the analyses carried out targeted the identification of

records that had the following characteristics: (1) significant cumulative production over the mine life: >0.15 Mt; (2) either active or closed operations were selected but separated in distinct groups (Table 4.4); (3) opportunities had to contain significant CRMs, and records with zero scores for SR_EI index were excluded; (4) opportunities with Mined_Mt as *NULL* value were excluded, since the query specifies a sorting in descending order to select the top deposits with the highest reported cumulative mined materials.

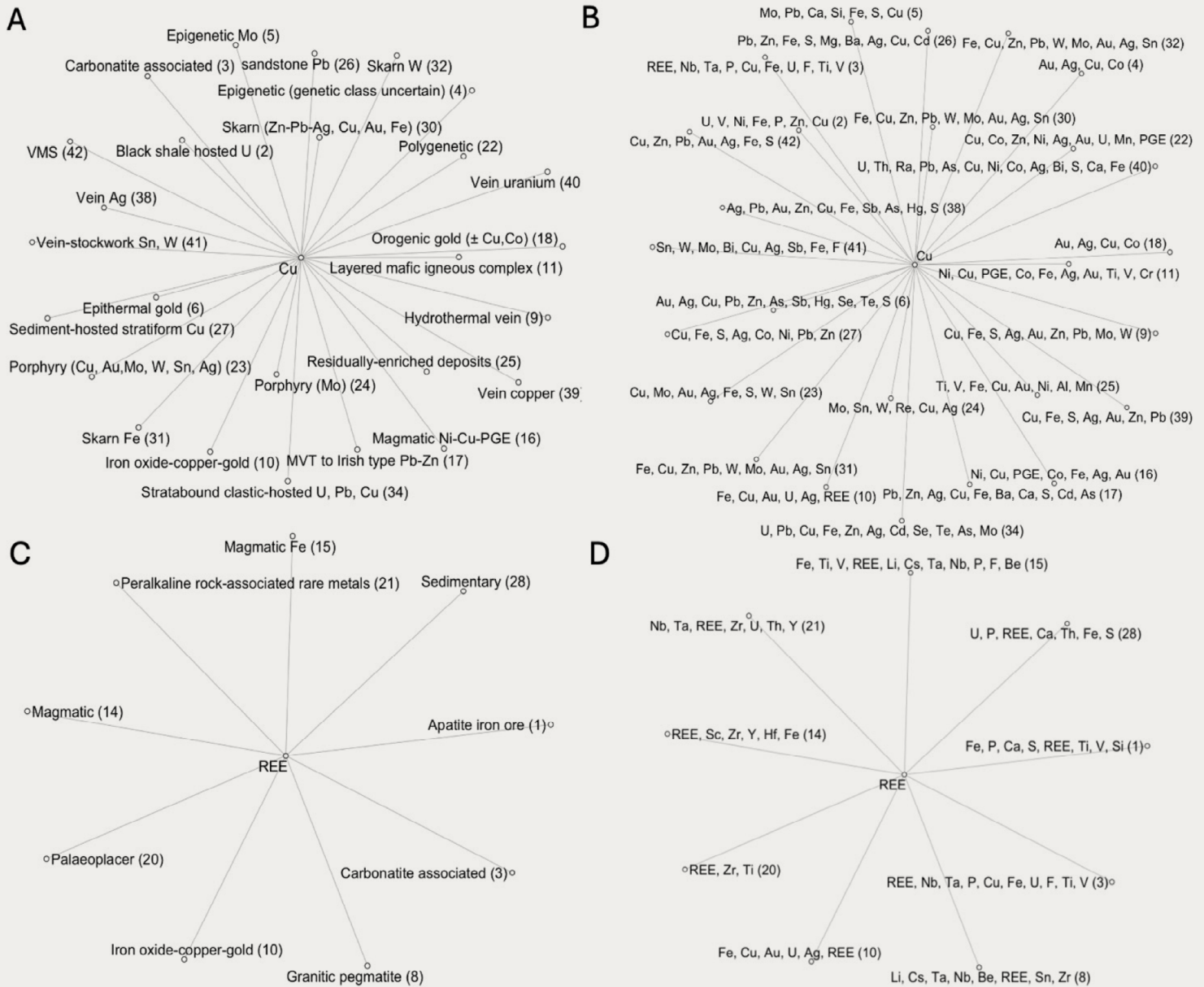


Figure 4.3. Ore genetic constraints adopted to filter CRMs that could be associated with specific mineral deposits and primary production metals in the NODD table. Graphs illustrating the associations of Cu and REEs with specific mineral deposit styles (A, B), and the corresponding common elemental associations (B, D). If a deposit produces specific primary metals (Cu in this example), several companion metals can be determined, representing multiple populations of elements; however, depending on the ore genetic style, only specific groups of elements or CRMs could be present as companions in the producing mines. The numeric indexing (n) facilitates the comparison of ore style with the corresponding metal associations (Epigenetic Mo; Mo, Pb, Ca, Si, Fe, S, Cu; 5).

Selection, Search and Sort are the main fields in the Adminer interface for SQL query development (Fig. 4.5); however, it is also possible to insert custom query statements to perform more complex analyses and data extractions involving logical statements that incorporate conditional logic (e.g., conditional "OR"; by default, SELECT SQL statements developed using the GUI do not allow an "OR" condition to be set in Adminer).

More complex SQLs allow (a) the selection of specific fields in the database, (b) a search for records that satisfy a set of conditions and ultimately (c) sorting of the sub-set according to specified field(s) in the database. In this example, we use primary resource records derived from the NODD integration together with NSCRMD indexing to evaluate the presence of tailings or other mining waste in opportunities that recorded over the 0.15 Mt of cumulative production. The results of the SQL analysis are documented in Table 4.4 for groups of countries and limiting the result to 10 records or less (e.g., Greenland cases) to summarise the top opportunities for active and historical projects (closed mines).

Table 4.3. Examples of SQL statements used to filter data sequentially for the definition of sites that would be interesting given their production history and inferred potential for CRMs. It is worth noting that the logical expression '!=' was used to select all statuses except 'Active mine' and thus it recovered records containing non-active operations (SQ1, 2). Examples SQ3, 4 instead selected the active mines to allow ranking of both types of operations in separate groups (closed vs active). 'LIMIT 50' simply returns 50 records in case the query finds more than 50 results. If less than 50 results are obtained, it will return the corresponding records.

SQL Query ID	SQL Statement	Comment
SQ1	<pre>SELECT "Name", "Latitude", "Longitude", "Mined Mt", "Size category", "Status", "Country", "SR FI score", "CRM rep", "Genetic type" FROM "nodd class10052024v1" WHERE "Mined_Mt" IS NOT NULL AND "Country" LIKE '%Fin%' AND "Status" != 'Active mine' AND "Mined_Mt" >= '0.15' ORDER BY "Mined_Mt" DESC LIMIT 50</pre>	Query designed to select Finnish top 50 inactive deposits with potential for waste material containing CRMs
SQ2	<pre>SELECT "Name", "Latitude", "Longitude", "Mined Mt", "Size category", "Status", "Country", "SR FI score", "CRM rep", "Genetic type" FROM "nodd class10052024v1" WHERE "Mined_Mt" IS NOT NULL AND "Country" LIKE '%Nor%' AND "Status" != 'Active mine' AND "Mined_Mt" >= '0.15' ORDER BY "Mined_Mt" DESC LIMIT 50</pre>	Query designed to select Norway's top 50 inactive deposits with potential for waste material containing CRMs
SQ3	<pre>SELECT "Name", "Latitude", "Longitude", "Mined Mt", "Size category", "Status", "Country", "SR FI score", "CRM rep", "Genetic type" FROM "nodd class10052024v1" WHERE "Mined_Mt" IS NOT NULL AND "Country" LIKE '%Swed%' AND "Status" = 'Active mine' AND "Mined_Mt" >= '0.15' ORDER BY "Mined_Mt" DESC LIMIT 50</pre>	Query designed to select Sweden's top 50 active deposits with potential for waste material containing CRMs
SQ4	<pre>SELECT "Name", "Latitude", "Longitude", "Mined Mt", "Size category", "Status", "Country", "SR FI score", "CRM rep", "Genetic type" FROM "nodd class10052024v1" WHERE "Mined_Mt" IS NOT NULL AND "Country" LIKE '%Gre%' AND "Status" = 'Active mine' AND "Mined_Mt" >= '0.15' ORDER BY "Mined_Mt" DESC LIMIT 50</pre>	Query designed to select Greenland's top 50 active deposits with potential for waste material containing CRMs

The advantage of obtaining summaries of this type is the possibility of ranking projects with mining waste from different perspectives connected with the classification strategy discussed earlier in section 4.1.1.3.

These opportunities span a range of deposit styles, and their waste associated with the level of production would probably include CRMs of interest, such as the strategic metals/minerals Ni, Cu, Ti, V and Co, as well as PGEs and REEs. Although these are summaries or extracts of primary resources, they are sorted according to the ore produced (cumulative production in Mt) and thus are likely to represent opportunities where significant mining waste could be exploited or remined (e.g., the Otanmäki project, one of the selected case studies in section 3.2, appeared to provide the best opportunity in terms of amount of mined material, with reasonable CRM potential in Finland). This consideration was validated by examination of the top ten projects generated by the search, as well as by considering the relational link that connects to the NSCRMD database, which provides a validation strategy for the identification of waste material with a higher degree of confidence (nscrm_nodd_idx field) (Fig. 4.5). Making this connection with the NSCRMD increases the degree of confidence that (if a specific site has information on secondary resources) tailing facilities or waste dumps will be in close vicinity or within the mine premises. This allows us to understand whether, for instance, mineral concentration occurred at a mine site or in a separate facility via direct consultation of the Nordic Database. The connection with NSCRMD finally offers a more detailed characterisation of the waste material.

The NSCRMD implementation allows the exploitation of a relational link to the source geochemical data that were used for numerical aggregation, and it is thus possible to increase even further the evaluation detail by obtaining, for example, information on the method and laboratory that was used to analyse

Language: English
PostgreSQL » database-nscrm-1.ce2tfuvx6fxt.eu-north-1.rds.amazonaws.com » NORDIC_DBS » Schema: public_nsp

Adminer 4.8.1

DB: NORDIC_DBS
Schema: public_nsp

SQL command
Import
Export
Create table

- Mined_mt_v1
- Recent Finnish Op
- Selection Query Top Prod Fin
- malmkemi_17032024
- nodd_01052024v2
- nodd_17032024
- nodd_17042024
- nodd_class10052024v1
- noddclass19032023v3
- noddgen_sc
- npit_15032024
- nscrm_17032024

Schema: public_nsp

Alter schema Database schema

Tables and views

Search data in tables (10)

Table	Engine	Collation	Data Length	Index Length	Data Free	Auto Increment	Rows	Comment
☐ Mined_mt_v1	table		65,536	40,960	?	?	1,527	
☐ Recent Finnish Op	Materialized view						?	
☐ Selection Query Top Prod Fin	Materialized view						?	
☐ malmkemi_17032024	table		499,712	49,152	?	?	1,484	
☐ nodd_01052024v2	table		2,416,640	286,720	?	?	1,527	
☐ nodd_17032024	table		1,138,688	221,184	?	?	1,526	
☐ nodd_17042024	table		2,392,064	73,728	?	?	1,526	
☐ nodd_class10052024v1	table		3,440,640	188,416	?	?	1,527	
☐ noddclass19032023v3	table		516,096	40,960	?	?	1,526	
☐ noddgen_sc	table		180,224	40,960	?	?	1,527	
☐ npit_15032024	table		73,728	212,992	?	?	50	
☐ nscrm_17032024	table		286,720	122,880	?	?	571	
12 in total		en_US.UTF-8	11,010,048	1,277,952	0			

Selected (0)

Vacuum Optimize Truncate Drop

Move to other database: public_nsp Move

Figure 4.4. Adminer interface with a list of relational tables, including multiple versions of NODD, NSCRMD and other resources and geochemical data.

Select: nodd_01052024v2

Select data Show structure Alter table New item

Select

- Name
- Latitude
- Longitude
- Mined_Mt
- Size_category
- Status
- Country
- Resource_reporting_standard
- nscrm_nodd_idx
- Main_metals
- Other_metals
- Genetic_type

Search

Mined_Mt IS NOT NULL

Country LIKE %Fin

Status != Active mine

(anywhere) =

Sort

Mined_Mt descending

Limit 10

Text length 100

Action Select

```
SELECT "Name", "Latitude", "Longitude", "Mined_Mt", "Size_category", "Status", "Country", "Resource_reporting_standard", "nscrm_nodd_idx", "Main_metals", "Other_metals", "Genetic_type" FROM nodd_01052024v2 WHERE "Mined_Mt" IS NOT NULL AND "Country" LIKE '%Fin%' AND "Status" != 'Active mine' ORDER BY "Mined_Mt" DESC LIMIT 10
```

Name	Latitude	Longitude	Mined_Mt	Size_category	Status	Country	Resource_reporting_standard	nscrm_nodd_idx	Main_metals	Other_metals	Genetic_type
Otanmäki	64.116704	27.100103	29.813	Large	Closed mine	Finland	Historic	B057	V,Fe,Ti	NA	Mafic intrusion-hosted Ti-Fe±V
Outokumpu	62.724461	28.991908	28.5	Large	Closed mine	Finland	Historic	B049	Cu,Co	Zn,Ni,Au,Ag	Polygenetic
Vihanti Zn	64.40659835	25.14417723	27.939	Large	Closed mine	Finland	Historic	B044	Zn,Cu	Au,Ag,Pb	VMS
Hitura	63.849667	25.046895	17.177362	Medium	Closed mine	Finland	Ni 43-101	B035	Ni,Cu	Co,PGE	Magmatic Ni-Cu-PGE
Mustavaara	65.814357	28.085154	13.446	Large	Closed mine	Finland	Ni 43-101	B060	V,Fe,Ti	NA	Mafic intrusion-hosted Ti-Fe±V
Kotalahti	62.575497	27.609041	12.35763	Medium	Closed mine	Finland	Historic	B039	Ni,Co	Cu	Magmatic Ni-Cu-PGE
Rautuvaara Mine	67.49992	23.93583	11.564	Medium	Closed mine	Finland	Historic	B010	Fe,Cu	NA	Iron oxide-copper-gold
Vammala	61.33408	23.027254	7.565368	Medium	Closed mine	Finland	JORC	B029	Ni,Co,Cu	NA	Magmatic Ni-Cu-PGE
Hammasmahti	62.46222929	30.03020578	7.2	Small	Closed mine	Finland	Historic	B047	Cu,Zn	Au,Ag	Sedimentary exhalative
Luikonlahti	62.941654	28.701783	6.983164	Medium	Closed mine	Finland	Historic	B053	Co,Cu,Ni	Zn	Polygenetic

Figure 4.5. Example of the selection query building process in Adminer. Select, Search and Sort fields were adjusted to construct extracts of the NODD data table. Selected fields were populated with deposits that had significant cumulative production and were either closed or active mines. The filtering allowed the identification of sites that are known to contain waste materials (e.g., case studies discussed in section 3.2).

the samples of tailings or any other waste material, providing a direct indication of the quality of analytical methods and other technical aspects (e.g., the number of elements considered in the geochemical investigation and when this was conducted; these aspects are essential to any QA/QC validation of the data imported in the database and used for the aggregation statistics).

4.1.1.5 CRM potential of historical mining projects

In evaluating the potential of various historical mining projects, several critical factors might be considered in a preliminary exploratory phase (not yet at the feasibility study stage, where the more rigorous methodology of resource estimation is implemented). Factors could include the type of ore deposit, mined tonnage and the complexity of metallurgical recovery. However, here, to provide emphasis on CRMs, we propose the embedding of a criticality score (SR_EI score). Some of these classification factors are included in Table 4.4. This comprehensive analysis examines promising historical mining projects focusing on REEs, copper (Cu), nickel (Ni), platinum group elements (PGEs) and cobalt (Co), with a detailed assessment of the criteria used to illustrate possible opportunity selection strategies.

The primary criteria include the mined tonnage (Mined_Mt), which indicates the historical scale of operations and remaining resource potential, the SR_EI score, which reflects a combined representation of economic importance and the supply risk of CRMs for each project, and the genetic type of the ore deposit, which influences the complexity and cost of metallurgical recovery (Gupta & Krishnamurthy 2005, Bragin 2006, Rabie 2007, Kuzmin et al. 2012, Kumari et al. 2015, Zhang et al. 2017, Šajin et al. 2022), as well as its RMR (Nassar et al. 2021). Additionally, the inclusion of a field representative of *predicted* critical raw materials (CRM_rep, Fig. 4.4) further guides the evaluation.

REE projects

Among the closed mines, Grängesberg (one of the case studies; see section 3) scores the highest, with a cumulative mined tonnage of 132.78 Mt and an SR_EI score of 343.68. This project, categorised under the apatite iron ore genetic type, contains phosphorus and REEs, alongside traces of manganese, vanadium and titanium, making it attractive. The beneficiation process for such deposits is well established, involving conventional crushing, grinding and magnetic separation to concentrate the iron ore, followed by flotation to recover apatite (Alemrajabi et al. 2017, 2018, Alemrajabi 2018, Chipakwe et al. 2021). The REEs are subsequently extracted from the apatite through chemical leaching, often using sulphuric acid or other reagents (Gupta & Krishnamurthy 2005). This sequence of steps is moderately complex and cost-effective, given the established nature of iron ore processing. Despite the simplicity of the outlined methodology, it is important to evaluate the dominant mineralogical host of the REEs. At Grängesberg, mineralogical studies have documented the redistribution (remobilisation) of REEs in response to hydrothermal processes, leading to the reprecipitation of REEs in secondary (post-apatite) silicates and phosphates (Jonsson et al. 2016; Casey et al. 2024). The increase in silicate-hosting REEs can affect metallurgical recoveries and thus would require detailed feasibility studies to understand and map the types of REE remobilisation and their spatial distribution in primary and secondary deposits.

Similarly, other apatite iron ore deposits, such as Tuolluvaara (25.00 Mt, 343.68 SR_EI), Luossavaara (21.16 Mt, 343.68 SR_EI), Risbergsfältet (20.36 Mt, 343.68 SR_EI) and Blötbergfältet (15.77 Mt, 343.68 SR_EI), represent potential opportunities for REE recovery, according to the results obtained. These projects share the same genetic type and similar processing pathways as Grängesberg, making them attractive for REE extraction due to their high criticality scores and moderate processing complexity. In contrast, the Rautuvaara Mine, with a mined tonnage of 11.56 Mt and an SR_EI score of 40.73, falls under the iron oxide–copper–gold (IOCG) genetic type, which involves more complex and costly processing due to the presence of multiple minerals containing REEs (Ehrig et al. 2013).

The results of the SQL and criticality evaluation of CRM potential are confirmed by the identification of existing initiatives already considering the recovery of apatite from tailings, such as the GRANGEX apatite project at Grängesberg. This project involves recycling old beneficiation sand from the closed Grängesberg mine to produce enriched apatite for the fertiliser industry and magnetite concentrate for steel production or industrial water treatment. (Section 3.2.5 provides further information on REE contents for this important Swedish resource.)

Copper (Cu) projects

When examining historical copper projects, Outokumpu stands out with a mined tonnage of 28.50 Mt and an SR_EI score of 415.40. This polygenetic deposit contains a variety of valuable metals, including copper, indium, PGEs, nickel, cobalt, germanium and gallium. The complexity of processing polygenetic deposits lies in their diverse mineralogy (similarly to IOCGs), requiring multiple extraction and purification steps, which increases processing costs (Gupta et al. 2002, Gupta & Krishnamurthy 2005). However, the potential value due to the diverse metal content is significant.

In comparison, Løkken, with a mined tonnage of 24.00 Mt and an SR_EI score of 190.44, represents a volcanogenic massive sulphide (VMS) deposit. VMS deposits are typically less complex to process than polygenetic deposits, utilising conventional flotation techniques to concentrate the sulphide minerals. This simpler metallurgical recovery process translates to lower overall costs, making Løkken a more economically viable option for Cu–Co co-extraction (Frenzel et al. 2019, Dehaine et al. 2021).

Nickel (Ni) projects

Among historical nickel projects, Hitura presents an interesting case with a mined tonnage of 17.18 Mt and an SR_EI score of 143.96. This project, classified under the magmatic Ni–Cu–PGE genetic type, contains nickel, copper, cobalt and PGEs. The beneficiation of magmatic deposits typically involves crushing, grinding and flotation to concentrate sulphide minerals, a process that is well established and moderately complex (Cole & Ferron 2002) because of the history of mining and economic importance of these and other mineral deposits (layered mafic–ultramafic intrusions), such as the South African examples (Von Gruenewaldt et al. 1985).

Other magmatic deposits include Kotalahti (12.36 Mt, 143.96 SR_EI) and Vammala (7.57 Mt, 143.96 SR_EI), which might share similar beneficiation methods and processing complexities, although significant mineralogical variation, even between distinct Ni–Cu–PGE domains in a single deposit, can lead to variable recovery rates (Cole & Ferron 2002), indicating that the proposed screening methodology represents a preliminary evaluation of the CRM potential.

In contrast, polygenetic deposits such as Outokumpu and Luikonlahti, with higher SR_EI scores but more complex processing requirements, may be less economically viable for nickel extraction due to the higher associated costs. Despite these considerations, polymetallic ores of this type show distinct end members (e.g., the Vuonos deposit) containing significant Ni mineralisation (Papunen 1987, Peltonen et al. 2008).

Platinum group element (PGE) projects

For PGE recovery, Hitura again emerges as important project, given its significant cumulative mined tonnage and good SR_EI score. Other magmatic deposits such as Kotalahti and Vammala also present viable opportunities for PGE extraction from associated waste, with similar processing pathways. Although PGEs are among the lowest in terms of concentration in disseminated ores at Vammala, they tend to be segregated in localised domains such as discrete As-rich veins (Gervilla et al. 2004).

Polygenetic deposits such as Outokumpu and Luikonlahti, while having high SR_EI scores and a diverse metal content, contain less PGEs, which were not recovered given the Ni-Co focus. Magmatic deposits are generally more economical for PGE extraction.

Cobalt (Co) projects

In the realm of cobalt projects, Løkken (Capella Minerals Ltd.) stands out, with a cumulative mined tonnage of 24.00 Mt and an SR_EI score of 190.44. As a VMS deposit, Løkken benefits from simpler processing methods, including conventional flotation techniques to concentrate the sulphide minerals (Taylor et al. 1986). This straightforward metallurgical recovery process translates to lower overall costs, making Løkken a highly economical option for cobalt co-extraction. The geometallurgical assessment of VMS deposits, such as the one conducted for Neves-Corvo (Frenzel et al. 2019), provides valuable insights into the mineralogical deportment and processing behaviour of additional by-product metals (e.g., In, Ge, Ga), demonstrating the potential for optimising recovery rates and reducing costs.



Table 4.4. Summary of the primary mineral resources identified as being prospective for CRMs and having a high likelihood of being associated with considerable amounts of secondary resources materials. The SR_EL score represents a multiplicative score obtained from the integration of the criticality assessment SR and EI scores (EU Commission 2023a). This score maps the criticality to individual deposits, offering additional discrimination capacity regarding the CRM potential. CRM_rep indicates predicted and reported CRMs constrained by companionship and ore genetic style logical rules. Curly brackets indicate CRMs reported in the NODD as other metals (see CRM_rep field).

Name	Latitude	Longitude	Mined_Mt	Size_category	Status	Country	SR_EL_score	CRM_rep	Genetic_type
Siiinjärvi	63,116	27,736	294,197	Large	Active mine	Finland	75	F, REE, P	Carbonatite associated (Cu, Fe, Ti, V, Nb-Ta, REE, U)
Kevitsa	67,699	26,965	83,701	Large	Active mine	Finland	144	Cu, PGE, Ni, Co	Magmatic Ni-Cu-PGE
Talvivaara	63,993	28,057	81,880	Very large	Active mine	Finland	549	Cu, In, Ni, Co, Ge, Mn, PGE, Ga	Polygenetic
Pyhäsalmi	63,659	26,046	61,903	Large	Active mine (Under Closure)	Finland	89	Cu, In, Ge, Ga	VMS
Kemi	65,787	24,711	61,174	Very large	Active mine	Finland	264	Mg, PGE, V, Ti	Mafic to ultramafic hosted Cr
Suurikuusikko	67,902	25,391	19,920	Large	Active mine	Finland	14	Cu, As	Orogenic gold (± Cu, Co)
Jokisivu	61,117	22,620	2,830	Medium	Active mine	Finland	14	Cu, As	Orogenic gold (± Cu, Co)
Taivaljärvi	63,941	29,048	2,448	Medium	Active mine	Finland	89	Cu, In, Ge, Ga	VMS
Pampalo	62,987	31,265	1,919	Small	Active mine	Finland	14	Cu, As	Orogenic gold (± Cu, Co)
Otanmäki	64,117	27,100	29,813	Large	Closed mine	Finland	40	V, Ti	Mafic intrusion-hosted Ti-Fe±V
Outokumpu	62,724	28,992	28,5	Large	Closed mine	Finland	415	Cu, In, PGE, Ni, Co, Ge, Ga	Polygenetic
Vihanti Zn	64,407	25,144	27,939	Large	Closed mine	Finland	89	Cu, In, Ge, Ga	VMS
Hitura	63,850	25,047	17,177	Medium	Closed mine	Finland	144	Cu, Ni, Co, PGE	Magmatic Ni-Cu-PGE
Mustavaara	65,814	28,085	13,446	Large	Closed mine	Finland	40	V, Ti	Mafic intrusion-hosted Ti-Fe±V
Kotalahti	62,575	27,609	12,358	Medium	Closed mine	Finland	144	Cu, Ni, Co, PGE	Magmatic Ni-Cu-PGE
Rautuvaara Mine	67,500	23,936	11,564	Medium	Closed mine	Finland	41	Cu, REE	Iron oxide-copper-gold
Vammala	61,334	23,027	7,565368	Medium	Closed mine	Finland	144	Cu, Ni, Co, PGE	Magmatic Ni-Cu-PGE
Hammaslahti	62,462	30,030	7,2	Small	Closed mine	Finland	89	{Cu}, In, Ge, Ga	Sedimentary exhalative
Luikonlahti	62,942	28,702	6,983	Medium	Closed mine	Finland	415	Cu, Ni, Co, In, Ge, PGE, Ga	Polygenetic
Black Angel	71,129	-51,229	11,2	Small	Closed mine	Greenland	139	Cu, As, In, Ge, Ga	MVT to Irish type Pb-Zn
Blyklippen	72,191	-24,123	0,544	Small	Closed mine	Greenland	14	Cu, As	Stratabound clastic-hosted U, Pb, Cu
Nalunaq	60,357	-44,840	0,423	Small	Closed mine	Greenland	14	Cu, As	Orogenic gold (± Cu, Co)
Tellnes	58,337	6,416	130	Large	Active mine	Norway	70	{Ni}, V, Ti	Mafic intrusion-hosted Ti-Fe±V
Ørtfjell	66,419	14,678	77,8	Large	Active mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Bjørnefjell	69,616	30,019	2,2	Small	Active mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron

Table 4.4. Cont.

Name	Latitude	Longitude	Mined_Mt	Size_category	Status	Country	SR_EI_score	CRM_rep	Genetic_type
Bjørnevatn	69,652	30,025	150	Large	Closed mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Fosdalen	64,080	11,209	35,5	Medium	Closed mine	Norway	90	Cu, {Co}, In, Ge	VMS
Løkken	63,122	9,698	24	Large	Closed mine	Norway	190	Cu, In, {Co}, Ge, Ga	VMS
Tverrdalen	69,622	30,031	23,5	Medium	Closed mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Ørtvann	66,409	14,535	17,6	Medium	Closed mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Tverrfjellet	62,227	9,509	15	Medium	Closed mine	Norway	89	Cu, In, Ge, Ga	VMS
Rødsand	62,844	8,123	15	Medium	Closed mine	Norway	40	V, Ti	Mafic intrusion-hosted Ti-Fe±V
Vesteråli	66,428	14,457	14,6	Medium	Closed mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Joma	64,853	13,885	11,453	Medium	Closed mine	Norway	89	In, Ge, Cu, Ga	VMS
Finnkåteng	66,425	14,438	10,7	Medium	Closed mine	Norway	128	Mn, Ni, V, Ti	Stratiform iron
Kirunavaara	67,833	20,190	1175,138	Very large	Active mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Aitik	67,072	20,959	987,315	Very large	Active mine	Sweden	26	Cu, In, Ge	Porphyry (Cu, Au, Mo, W, Sn, Ag)
Malmberget	67,185	20,673	632,376	Very large	Active mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Leveäniemi	67,633	21,026	89,319	Large	Active mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Garpenbergsfältet	60,316	16,207	64,227	Large	Active mine	Sweden	89	Cu, In, Ge, Ga	Skarn (Zn-Pb-Ag, Cu, Au, Fe)
Zinkgruvan	58,815	15,104	46,583	Large	Active mine	Sweden	89	{Cu}, In, Ge, Ga	Sedimentary exhalative
Tapuli	67,417	23,334	34,638	Medium	Active mine	Sweden	89	(Cu, In, Ge, Ga)*	Skarn (Zn-Pb-Ag, Cu, Au, Fe)
Kristineberg	65,063	18,567	34,071	Large	Active mine	Sweden	158	Cu, In, Ge, {Sb}, Ga	VMS
Björkdal	64,931	20,590	30,296	Large	Active mine	Sweden	14	Cu, As	Orogenic gold (± Cu, Co)
Renström	64,924	20,095	15,596	Large	Active mine	Sweden	158	Cu, In, {Sb}, Ge, Ga	VMS
Grängesberg	60,083	14,997	132,781	Large	Closed mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Laisvall	66,146	17,156	64,487	Large	Closed mine	Sweden	89	Cu, In, Ge, Ga	Sandstone Pb
Dannemorafältet	60,204	17,860	34,261	Large	Closed mine	Sweden	126	{Mn}, In, Ge, Ga	Skarn (Zn-Pb-Ag, Cu, Au, Fe)
Stråssa	59,748	15,200	28,060	Medium	Closed mine	Sweden	128	Mn, Ni, V, Ti	Stratiform iron
Tuolluvaara	67,854	20,320	25,000	Medium	Closed mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Luossavaara	67,873	20,222	21,157	Medium	Closed mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Risbergsfältet	60,087	14,998	20,363	Medium	Closed mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore
Håksberg-Ikorrbottn-Ivikenfälten	60,196	15,201	19,474	Large	Closed mine	Sweden	128	Mn, Ni, V, Ti	Stratiform iron
Norrberg-Morberg-Kallmorbergsfälten	60,083	15,943	19,022	Medium	Closed mine	Sweden	153	Ni, {Cu}, Mn, V, Ti	Stratiform iron
Blötbergsfältet	60,124	15,080	15,770	Medium	Closed mine	Sweden	344	{Mn}, V, Ti, P, REE	Apatite iron ore

4.2 Classification of primary and secondary resources

Global economic growth and development heavily rely on the metal output and industrial minerals supply (Valenta et al. 2019). Economic valuation of mineral deposits is intimately connected to supply chains and has evolved significantly to support decision-making processes. This section of the report focuses on non-spatial ore deposit/prospect valuation methodologies, excluding kriging and other spatial interpolation strategies (Bartier & Keller 1996, Chilès & Desassis 2018, Liu et al. 2023). We discuss a methodology typically used when limited information is available on the 3D variation of mineral/metal grades. For instance, global data on ore deposits are represented by average grades and tonnages of mineral resources, representing aggregated and coarser statistics from more detailed mineral resources estimates. These data summaries can be used to group (classify) deposits and mineral waste according to their value estimate.

In the broader context of orebody valuation, particularly for complex, polymetallic deposits, we explore the use of metal equivalents to facilitate the economic assessment of a project (Goldie & Tredger 1991, JORC 2012, Rose & Fahey 2019). For example, metal equivalents can be utilised to compare different ore deposits or their characterised waste materials. An application to the Nordic countries providing a common economic value denominator is given, despite inherent limitations in capturing the true value. Another simple application to secondary resources data is also provided. These examples illustrate the possibility of tuning the metal equivalents methodology to the problem of evaluation of CRM budgets by considering calculations that, for instance, exclude main production metals to focus attention on the potential of by-products.

4.2.1 Methodology used for the economic valuation of ore deposits and mining waste

Many mineral deposits produce (or have the potential to produce) more than one economic product. These products can be either in the form of metal concentrates or mineral concentrates. Thus, the concept of metal equivalents is both applicable to metals and industrial minerals, although their use has been predominantly in metal mining (Cu-, Au-, Ni-equivalent, etc.). Metal equivalents are used to summarise the values of multiple products into a single figure that represents the sum of the products usually expressed as the main metal/mineral considered (e.g., Cu-equivalent, or Au-equivalent if the considered mines are main producers of Cu and Au respectively). Metal equivalents can also be termed 'grade equivalents' (Rose & Fahey 2019). Methods for calculating the metal equivalent are reported in the literature (Annels 1991, Rose & Fahey 2019, Wang et al. 2023). Further to this, the JORC Code 2012 Edition in Clause 50 (JORC 2012) clearly sets out the reporting requirements in case a company decides to report grade equivalents under five criteria:

- Individual grades for all the metals considered in the metal eq. calculation should be included;
- In addition, the information provided by an exploration/mining company should include the assumed commodity prices;
- The relative metallurgical recoveries for all metals (or estimates and the estimation methodology) should be used and discussed;
- Inclusion of a clear statement discussing the potential for all included elements to be sold on the market is also mandatory;
- A final requirement is to provide an illustration of the calculation formula adopted.

Annels (Annels 1991, Rose & Fahey 2019) provides an example of the calculation of copper equivalents (CuEq) in a copper–molybdenum porphyry deposit:

$$CuEq = (Cu_{tot} \% - Cu_{as} \%) + ((NSR_{Mo} * molybdenum\ recovery) / NSR_{Cu} * concentration\ copper\ recovery * smelter\ recovery\ for\ copper) * Mo\%$$

Where Cu_{tot} is the total copper grade, Cu_{as} is the copper acid-soluble grade, NSR_{Mo} is the net smelter return price for molybdenum and NSR_{Cu} is the net smelter return price for copper. This example includes a differentiation between valuable and non-valuable copper mineralisation, and allowance for differences in metal prices and in metal recoveries. The equation represents and aggregation strategy that allows the value of an ore block to be expressed with a single value estimate. The advantage is that this common basis of reference can be used to compare different styles of polymetallic deposits.

4.2.2 Application of the metal equivalent methodology to the Nordic Database

The example presented determines the value of ore in a single project, illustrating the benefits of considering co-products and allowing the estimation of the *in situ* resource value inclusive of these additional revenue products, such as molybdenum. However, this is not the only way of using metal equivalents. Another important advantage is that metal equivalents allow the comparison of multiple ore deposits, even if they have different polymetallic associations, since a unique denominator is used. In this context, we discuss an example of a state-of-the-art application to Ni–Cu–PGE global data to illustrate the valuation strategy applied to these data and document the workflow adopted to define the role of by-products in ore deposits located in the Nordic countries. By-products can influence the results of comparative analysis for the purpose of ranking or classification of ore deposits and waste materials (section 4.1). This type of analysis is particularly useful if an attempt is made at re-evaluating historical projects, especially when attempting an estimation of the impact that CRM contents might have on an operation, both on its primary and secondary resources. Some examples are given to clarify the approach (or resource classification workflow).

4.2.2.1 Comparative analysis based on metal equivalents

Peck & Huminicki (2016) provide further insights into the advantages of a value-based analysis of global data on ore deposits, in analogy to what is proposed in this application to the Nordic examples. They remark that this is a more holistic view that can guide mineral exploration for mafic to ultramafic,

magmatic ore deposits, since the use of metal equivalents had allowed them to consider a larger range of known mineralisation styles, settings and commodities, even though their analysis focused on Ni–Cu–PGE deposits.

Value creation in this regard is obtained by the expansion of conventional exploration targeting strategies, which would significantly increase exploration areas. This is due to the inclusion of by-products in the valuation process. In their comparative approach, the authors provide an equivalent basis for the main metals and define an estimate of the net smelter returns (NSR), based on a pre-defined set of assumptions given the fact that Ni–Cu–PGE operations have different stages of development and thus not all data will be at disposal to perform accurate NSR calculations. NSR calculations represent an alternative model to metal equivalent estimates, but the two can be blended in hybrid solutions, as in this example from Peck & Huminicki (2016) (see Table 4.5).

In a global dataset, the availability of information is also regionalised, since distinct legal reporting requirements for operators are enforced. One example is the reporting of transport costs, recovery factors and smelter payability factors, which are frequently unreported for non-Western operations (Goldie & Tredger 1991). Table 4.5 reports estimates for the NSR factors, and the

Table 4.5. Summary of the equations and factors used in NSR calculations (modified from Peck and Huminicki 2016).

Commodity	Recovery	Payability	Price (\$US)	Price unit	Grade unit	NSR factor	Transport (\$US)
Copper	85%	90%	7322	Tonne	%	56,02	5
Nickel (sulfide)	70%	90%	15007	Tonne	%	94,54	5
Nickel (laterite)	95%	90%	15007	Tonne	%	128,31	5
Cobalt (sulfide)	70%	50%	26455	Tonne	%	92,59	5
Cobalt (laterite)	95%	90%	26455	Tonne	%	226,19	5
Platinum	85%	90%	1490	Troy ounce	g/t	36,65	5
Palladium	85%	90%	727	Troy ounce	g/t	17,88	5
Rhodium	85%	80%	1067	Troy ounce	g/t	23,33	5
Gold	85%	90%	1411	Troy ounce	g/t	34,71	5
Silver	85%	80%	23,8	Troy ounce	g/t	0,52	5
Lead	85%	90%	1908	Tonne	%	14,59	5
Zinc	85%	90%	1910	Tonne	%	14,61	5
Molybdenum	85%	90%	28307	Tonne	%	144,34	5

NSR calculation for Ni-Cu sulphide and PGE deposits

NSR value (US\$ per tonne of ore) = (Cu * 56.02 + Ni * 94.54 + Au * 34.71 + Pt * 36.65 + Pd * 17.88 + Rh * 23.33 + Ag * 0.52) - 5

NSR calculation for Ni(Co) laterite deposits

NSR value (US\$ per tonne of ore) = (Ni * 128.31 + Co * 226.19) - 5

NSR calculation for Cu deposits not related to mafic-ultramafic rocks

NSR value (US\$ per tonne of ore) =

(Cu * 56.02 + Co * 92.59 + Au * 34.71 + Pt * 36.65 + Pd * 17.88 + Rh * 23.33 + Ag * 0.52 + Pb * 14.59 + Zn * 14.61 + Mo * 144.34) - 5

equations utilised for illustrative purposes (Peck & Huminicki 2016). This methodology of global evaluation was also extended to the Nordic Ore Deposit Database in a simplified form that assumed 100% recovery rates and does not account for external 'out of the mine' costs (Eilu et al. 2007).

The Nordic Ore Deposit Database, formerly known as the Fennoscandian Ore Deposit Database (FODD), contains data on more than 1,500 metal mines and almost 500 industrial deposits (Eilu et al. 2007). In terms of geographical coverage, the database includes the Precambrian shield and the Caledonides, spanning Norway, Sweden, Finland, Greenland and Estonia. Data relating to Russia were removed because of the current geopolitical conditions since 2022. Information on the mineral deposits is detailed with historical and current mineral resource records and mineral/metal production statistics.

In the database, the use of metal equivalents has been considered to obtain estimates of the *in situ* value of the resources with a relatively simple calculation that considers 100% recovery rates. In this case, the crude estimates were useful to compare deposits that are very distinct, both in their polymetallic budget and genetically, since the classification has been extended to all styles of mineralisation (Fig. 4.7 provides an illustration of the deposit's size determination in the database, based on a 5-class categorisation of the CuEq estimates obtained using the last Q4 2023 commodity pricing data to compute respective tonnage equivalents).

The fact that recovery rates and costs are not accounted for represents a significant limitation of these value estimates, even though their purpose is dedicated to defining a classification system that discriminates deposits based on their size. The term 'size' might be subject to misinterpretation, especially when dealing with deposits of extremely rare metals with very high rock-to-metal ratios (RMR) (Nassar et al. 2021, see Fig. 4.6), where the volume/mass of the metal/mineral of interest is often comparatively small but of considerable value. Therefore, in this example, it becomes clear that the significance of classifications defining the 'size' of an ore deposit can be better represented by calculating and creating thresholding classes that refer to the *in situ* value of the resource (inclusive of co- and by-products) expressed in monetary or metal equivalent form.

If we consider the calculation in more detail, in this case it simply multiplies grade by tonnage and metal price. The figures as mentioned are to be considered estimates (approximations), since the standards for reporting mineral resources and production are highly heterogeneous both in the methodology of calculations carried out in different times (hence different metal pricing and cut-off grades) and with different reporting standards (e.g., NI 43-101 or the JORC codes). *In situ* calculations are not to be considered as ore reserve estimates, which are based on international standards (Eilu et al. 2007).

The metal prices used in the calculation are represented by 10-yr averages for the period 2013–2022 of the annual averages of spot market prices, and an average of Q4 2023 prices. For metals and minerals, prices were derived from various sources. For metals that are traded on a metal exchange (e.g., the London Metal Exchange, LME), it is sufficient to directly collect the price values. Other prices for commodities that are non-listed were derived from other reputable sources (e.g., the Morocco market price for phosphate rock, the International Monetary Fund for renewables and the USGS Mineral Commodity Summaries for 2023).

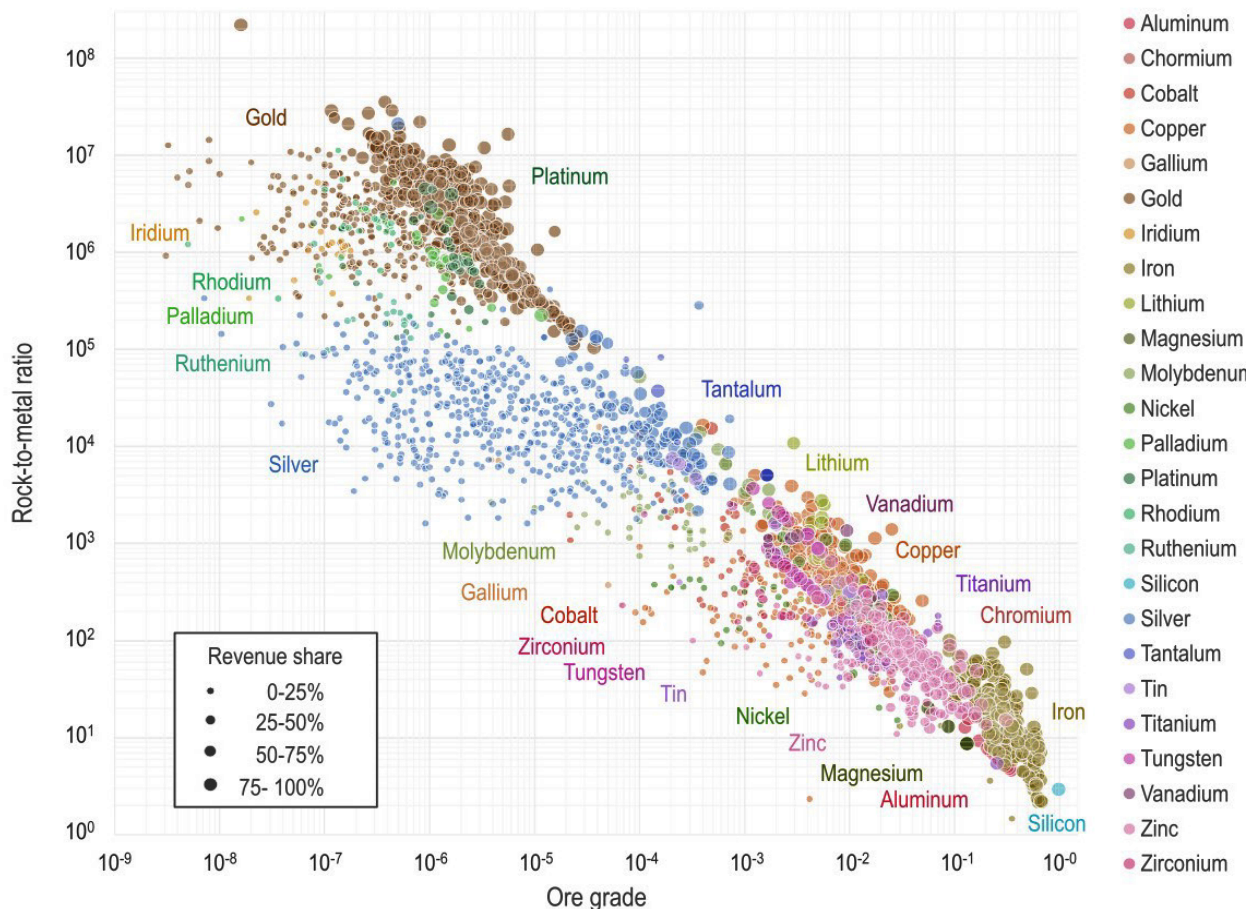


Figure 4.6. Rock-to-metal ratio (vertical axis) versus ore grade (horizontal axis) by mineral commodity and individual operations with variable revenue shares, adapted from Nassar et al. (2021).

4.2.3 Classification results and implications for the primary and secondary CRM potential in the Nordics

In this application of metal equivalents, we consider CuEq as a basis, since the objective of the analysis is to have a common reference for the comparison of multiple deposits (even if the deposits are not mined for Cu), and copper is commonly used as a reference due to its relatively stable price. This is an assumption that introduces bias in the analysis and represents a limitation of the metal equivalents method. Using copper prices as the denominator in the metal equivalent calculation renders the analysis particularly sensitive to copper price variations. If copper pricing remains stable over time, there would be no significant change in the valuation of an ore deposit; however, any price volatility could dramatically change the impact that by-products have on the value estimate, since their value is expressed in CuEq. The higher the Cu price, the lower would be their impact on the total *in situ* resource value.

The calculation was extended to all the mineral resources reported in the NODD database and geographically limited to Norway, Sweden and Finland. The objectives for this analysis considered: (a) the determination of the impact of different commodity pricing models from a multiyear average (more robust) compared with average prices for Q4 2023, and (b) as already discussed, evaluation of the potential of by-products as additional contributors to the value of the deposits. A final objective (c) considered the standardisation of the calculation methodology.

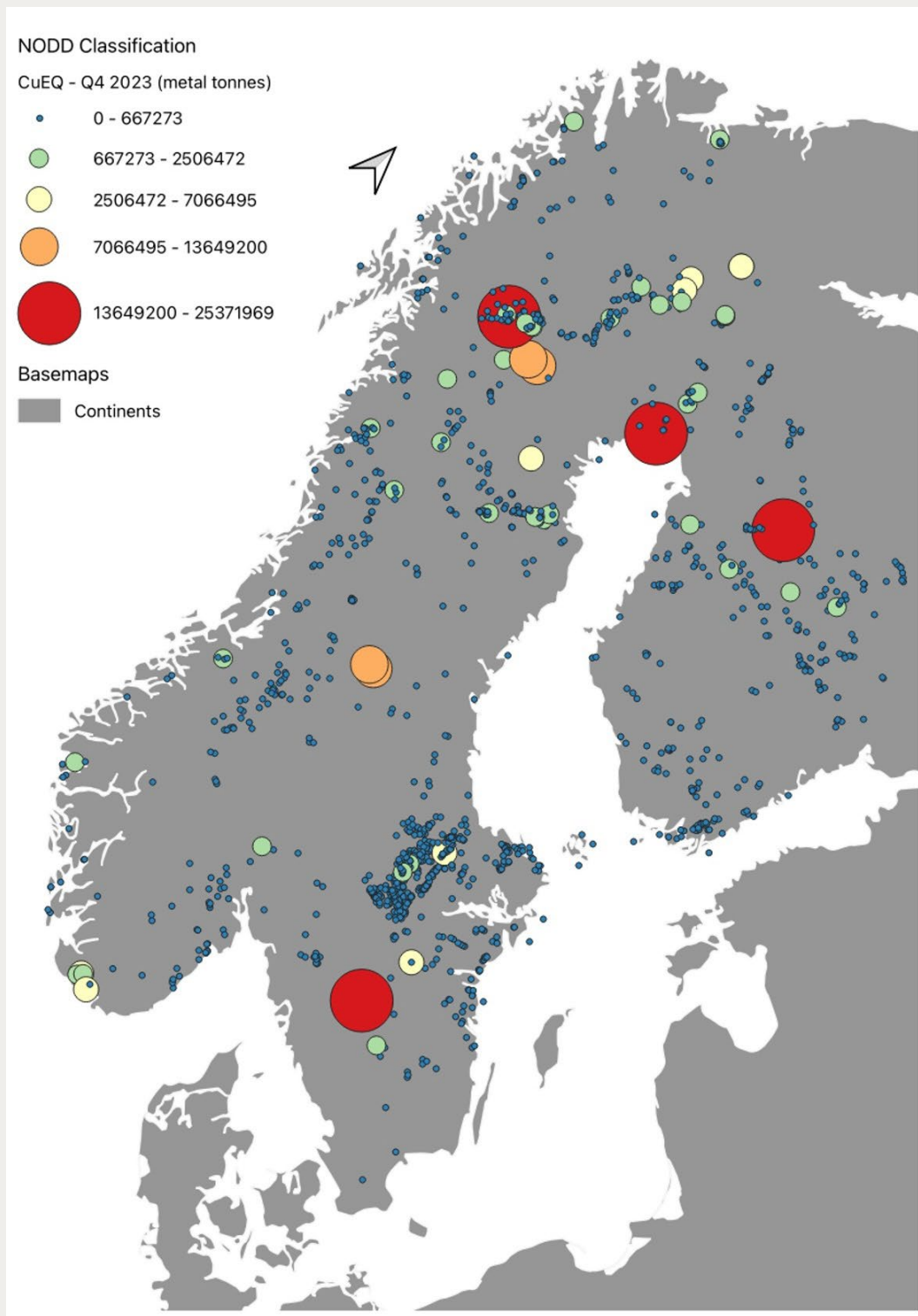


Figure 4.7. Classification of mineral deposits in Nordic countries based on estimates of CuEq (tonnes) using the Q4 avg. of 2023 commodity prices. Data expressed as tonnes of Cu metal equivalent. The classes defined differ from the convention adopted for the determination of group categories in the NODD deposit size classification. Natural breaks classification with 5 size categories was used to enhance group separation (Jenks 1967).

4.2.3.1 Primary ores

Metal equivalent calculations are reported for some of the most important ore deposits in the Nordic countries, based on the two pricing averages considered (10 yrs 2023–2013 vs Q4 of 2023) and other deposit-specific mineral resource estimates (average grades and total tonnages) (see Annex B). Table 4.6 illustrates the effect of using different pricing averages of commodities, visible in the relative variation in metal factors and resulting in significant variation in the estimated CuEq tonnes of metal. For this example, ten of the major deposits from all the considered Nordic countries were used to evaluate how commodity prices can impact the copper metal tonnage estimate (EqCu Mt fields presented in Annex B).

The following deposits were considered: Talvivaara, Kirunavaara, Kemi, Malmberget, Aitik, Tellnes, Ørtfjell, Bjørnevatn, Siilinjärvi and Gruvberget. The deposits represent examples of polymetallic and monometallic mineralisation and a variety of mineral deposit styles and relative metal associations. They are mostly represented by base metals, except for Talvivaara and Aitik, which contain both base and precious metals, and Siilinjärvi, which mainly contains phosphate rock (the rock contains apatite, an industrial mineral rich in phosphorus). For each deposit, metal factors were determined using a formula that converts the metal tonnes of non-Cu resources into a CuEq estimate. Table 4.6, with the included equations, presents an example of the calculation performed to estimate the metal factors for the Aitik polymetallic deposit in Sweden.

Table 4.6. Aitik tonnage and grade (2023 data derived from the NODD database).

Aitik Tonnage and Grades	Mt	Cu %	Zn %	Pb %	Au ppm	Ag ppm
	3,265.315	0.231	0.008	0.028	0.134	1.54

$Cu\ mt\ (*) = total\ tonnage * Cu\ grade = 7,317,744\ t$

$Zn\ mt = total\ tonnage * Zn\ grade = 257,724\ t$

$Pb\ mt = total\ tonnage * Pb\ grade = 898,393\ t$

$Au\ mt = total\ tonnage * Au\ grade = 437\ t$

$Ag\ mt = total\ tonnage * Ag\ grade = 5029\ t$

*Contained metal tonnes of the respective commodity.

Additional analyses (Fig. 4.8, A, B) consider an evaluation of the by-product potential for polymetallic deposits. To fulfil this objective, the calculation of CuEq tonnes was carried out with different input data. A first calculation (as presented earlier in the Aitik deposit example) was based on all the polymetallic assemblage (the main production metals combined with co- and by-products). Subsequently, the calculation was constrained to only the main metals (Cu and Au for Aitik). This approach allowed the contrasting of these results, as illustrated in Figure 4.8, B. The difference in CuEq tonnage was presented to illustrate the upgrading effect that occurs if by-products are accounted for in the metal equivalent calculation. Figure 4.8 proposes a comparison with the NODD deposit size classification. The purpose is to illustrate how the two maps offer a different perspective on the mineral potential and provide a more comprehensive evaluation of the deposit's characteristics.

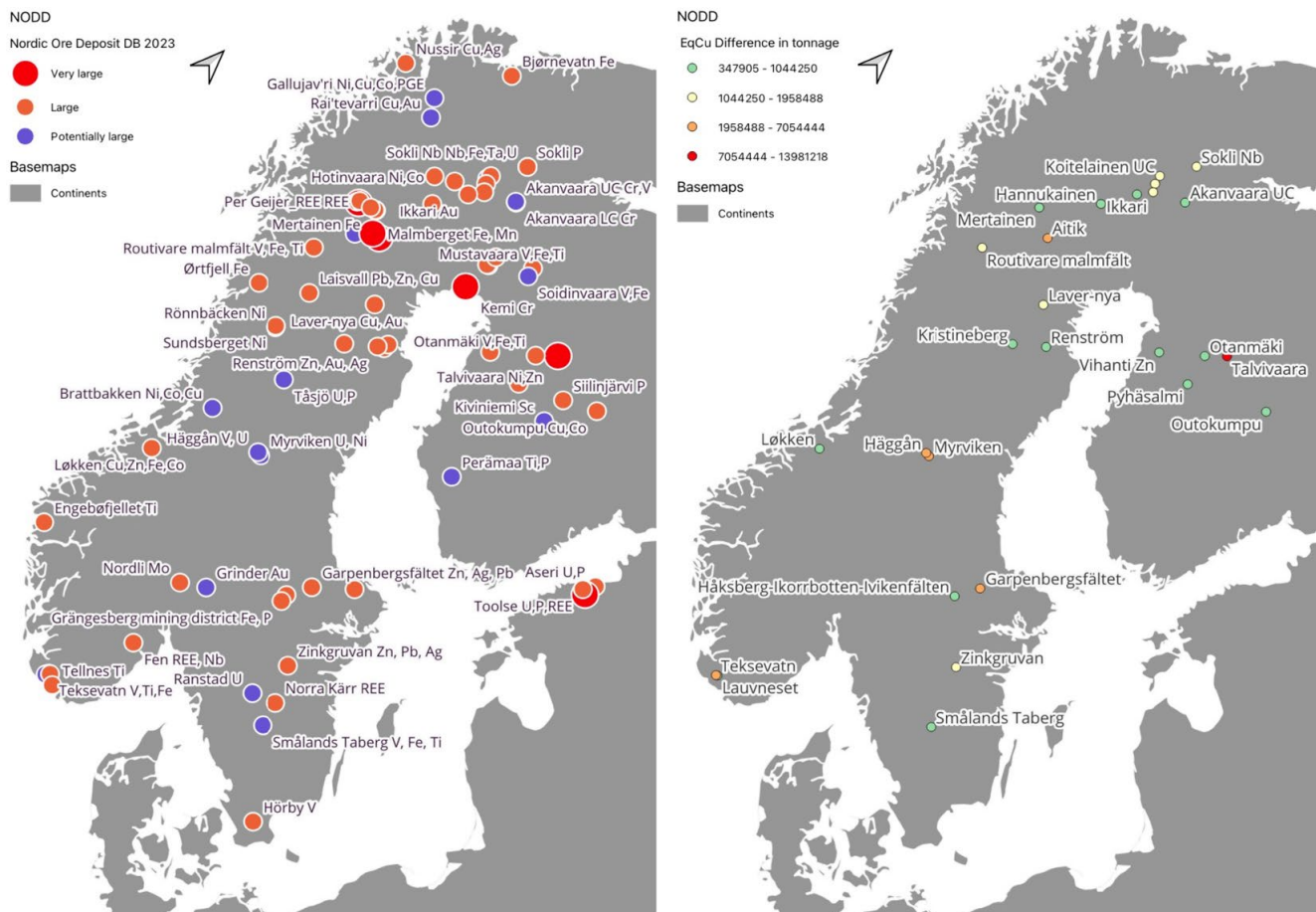


Figure 4.8. Examples of mineral deposit classifications adopted in the NODD analysis. A) An illustration of the classification based on the mineral deposit size (selected sizes are presented to emphasise some of the most important deposits in the Nordic countries). B) An illustration of the difference in CuEq estimates obtained by considering the main metals only or both main and by-product metals and minerals in the CuEq calculation. For case B classification and grouping, it is significant to evaluate the by-product potential. In this case, the monometallic ores are not considered, and it is possible to evaluate which resources are more likely to be important for by-product contents. One example is Talvivaara, which is classified in the NODD as having as the first production metal its nickel production. However, this deposit is notably enriched in zinc and historically produced significant zinc and cobalt ores.

Economic significance (size) in the NODD classification (Fig. 4.8, A) defines the value of different ore deposits holistically. Instead, an alternative calculation of the by-product potential (Fig. 4.8, B) can be interpreted as a classification that flags deposits where by-products play a major role in their economic valuation. This interpretation is essential to valuations that attempt to infer risks and opportunities associated with specific by-product commodities that are known to be subject to significant price fluctuations (e.g., U, Li, REEs, Ge, In, Ga and other CRMs of concern).

4.2.3.2 Mining waste valuation

The examples discussed to date are important for the qualification of sites that have a polymetallic nature and could contain significant amounts of CRMs in primary ores. Global analyses of this type are also useful, although indirectly, to target secondary resources with CRM potential. Any mineral deposit that has entered production (in the order of several million tonnes of ore mined annually) has led to significant waste accumulations commonly stored

in tailings facilities and rock dumps. These secondary materials will likely contain CRMs and other valuable metals, as the waste is often still enriched in primary ores (Lottermoser 2003).

If we consider a more direct valuation approach for the tailings, this will require a good level of resource definition and, similarly to an ore deposit, a mineral resource estimate with a cut-off grade and relative tonnage. This information is often of poor quality and seldom reported for mining waste (Mudd & Jowitt 2018). Despite the challenges, with the objective of extending the metal equivalent workflow to secondary resource data, we consider a sub-set of the NSCRMD table represented by a group of Finnish mines with up-to-date data on the mineral waste (Kinnunen et al. 2022) and document their CRM budgets (Fig. 4.9). Because of the uncertainty in the continuity and distributions of CRMs in these secondary deposits, the results should only be considered as an example of how valuations can be carried out to obtain preliminary comparisons of the CRM potential. More comprehensive data on the calculations performed on 19 operating and closed/historical sites with reported waste and geochemical compositions are reported in Annex C. The results obtained compare the distribution of value in tailings from the top 9 operations in order of economic significance of the tailings in Annex C and Figure 4.9, showing the distribution of shares of value in a set of considered commodities inclusive of strategic CRMs such as Ni, Cu, Ti, Co and Mn.

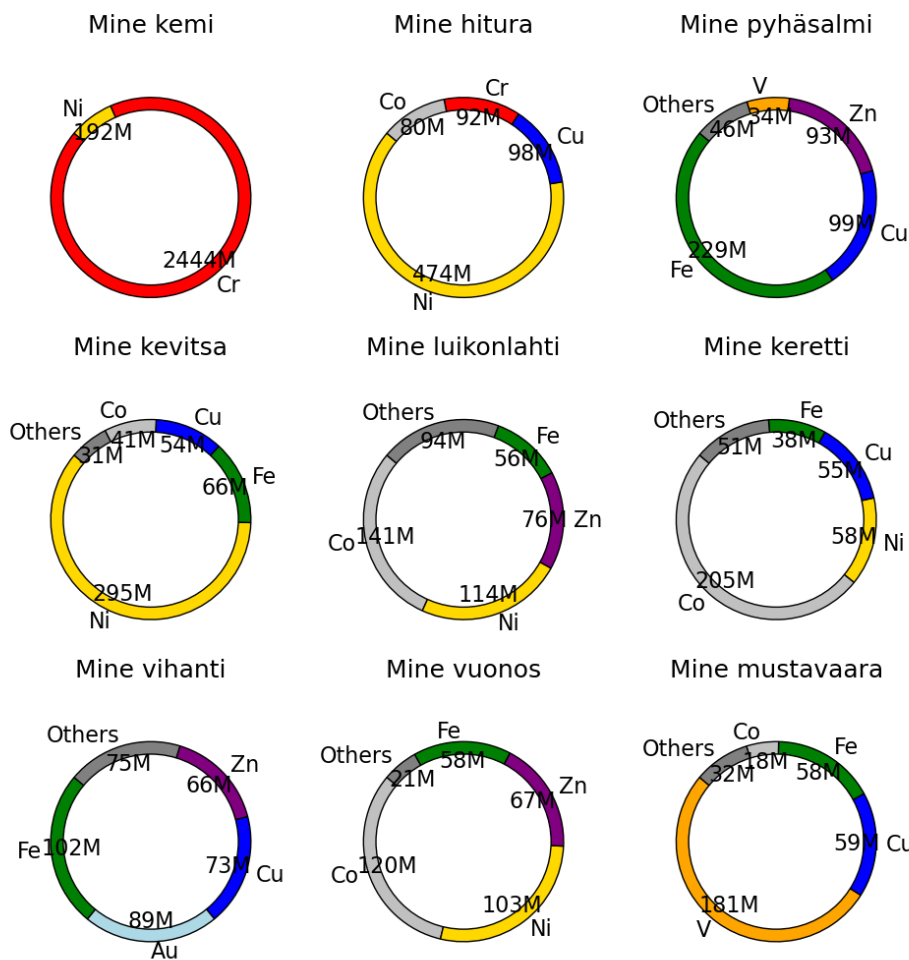


Figure 4.9. Summary of values in USD of metal contents in Finnish tailings (estimated, non-compliant). The top 9 tailings by value are reported in the image out of 19 cases considered (Annex C). Circle plots illustrate the proportion of contributions from each metal. There is significant heterogeneity in the CRM budgets and relative proportions observed. The Kemi estimate resulted in the most valuable waste. The valuation was restricted to metals that are commonly recovered during smelting of the ores either as primary metals or as co- or by-products.

5 Discussion and conclusions

This section revisits key concepts discussed in the main sections. It also discusses the implications of the results of the case studies (Section 3) and the advancements in data management, classification and related developments presented earlier (Section 4).

An initial survey of the macroeconomic factors affecting the consumption and pricing of raw materials exposed some of the weaknesses of modern globalised economies. Financial tightening in response to abnormal inflation and the effect of recent conflicts in Ukraine and in the Middle East had significant effects on energy and commodity prices. These and other macroeconomic factors can induce market volatility (e.g., rapid increases in commodity prices, Fig. 5.1), increasing the likelihood of economic slowdowns or recessions (Pindyck 1984, Schwert 1989). Financial policy is used to stabilise markets with the expectation of improved economic conditions. However, this stabilising action extends further with a host of policies connected to raw materials and their supply chains.

The CRM Act together with the Net Zero Industry Act are tangible examples of these initiatives to support European economies (under the Green Deal Industrial Plan), reducing supply chain risks by enacting the diversification of trade and promoting circularity to offer a more sustainable management of natural resources. The Nordic Innovation Program/Project embraced and aligned with this EU strategy. The results presented in this report represent a direct contribution to these actions dedicated to the valorisation of mining and industrial waste.

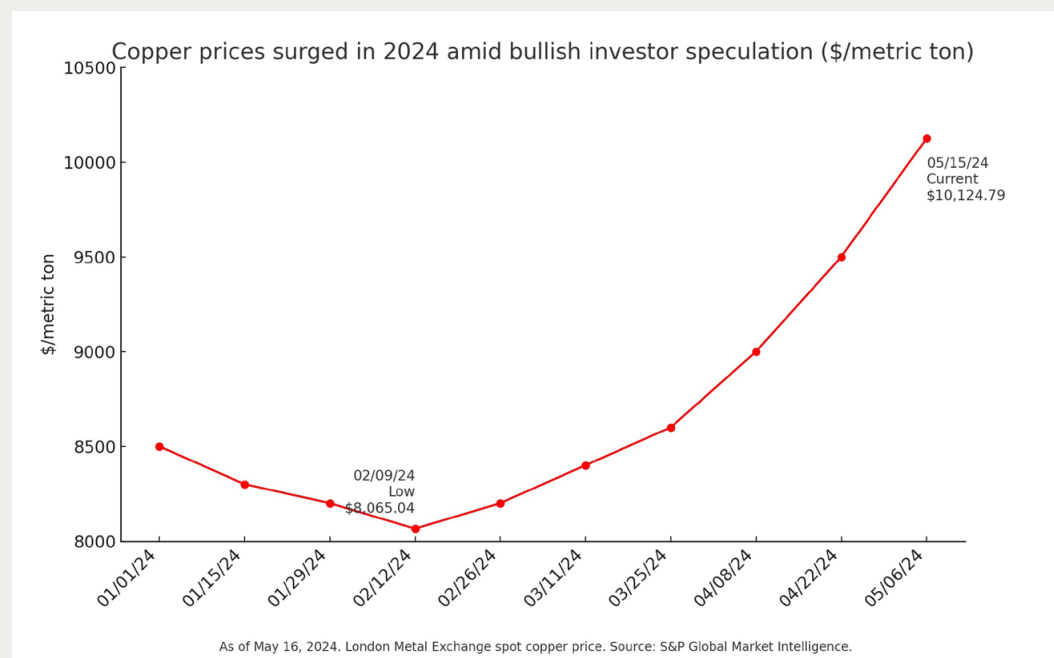


Figure 5.1. Diagram illustrating the variation in the copper price (January–May 2024 period). The price stabilised in the initial part of the year to then rebound significantly, entering speculative territory in mid-2024 (S&P Global, LME spot prices).

The research streams considered a multiscale approach represented by detailed studies of key localities renowned for their secondary mineral resource potential, and the development of resources that could facilitate the management and classification of primary and secondary raw materials. The research conducted was multidisciplinary, addressing a variety of fields and applications from classic geological studies involving mining waste to more engineering-focused analyses, targeting the characterisation of industrial waste in more advanced stages of the mineral/metal production and energy (only with reference to urban waste management) supply chains.

Considerations from the case studies

Detailed case studies conducted in Finland (Aijala, Kaustinen, Otanmäki, Talvivaara), Sweden (Grängesberg, Yxsjöberg), Norway (Folldal, Løkken), Iceland (Grundartangi) and Denmark (Roskilde, Lisbjerg) provided valuable insights into the CRM potential of mining and industrial waste. These studies underscore the critical importance of site-specific investigations for accurate CRM assessment and recovery planning. However, they also emphasised the importance of community acceptance and embedding of ESG practice(s) in current re-mining projects.

In Finland, the case studies at Aijala, Kaustinen, Otanmäki and Talvivaara highlighted significant opportunities for CRM recovery. At Aijala and Otanmäki, re-mining of tailings is a primary focus. Talvivaara and Kaustinen are also proposing innovative circular economy solutions. Public acceptance and ESG issues were integral to these studies. For instance, in Aijala, there is public support for re-mining activities, although environmental concerns remain a priority.

Sweden's case studies in Grängesberg and Yxsjöberg demonstrated CRM diversity. The Grängesberg mine, notable for its large cumulative mined tonnage, presents a significant opportunity for the recovery of REEs. Geochemical analyses of tailings at Grängesberg revealed substantial concentrations of REEs, particularly neodymium and dysprosium, which are critical for high-tech applications. Yxsjöberg, with its extensive tailings, has tungsten, copper and fluorite, offering substantial potential for CRM extraction. Tungsten and copper are essential for various industrial applications, including electronics and renewable energy technologies.

In Norway, the Folldal and Løkken case studies provided valuable insights into the CRM potential of tailings from historical mining activities. The Løkken site, known for its volcanogenic massive sulphide (VMS) deposits, has significant quantities of copper, zinc and cobalt with minor elements such as indium and gallium, which have high economic value and are crucial for electronics and green technologies. The Folldal site, with its historical mining of copper and zinc, also could hold considerable CRM potential in its sludge and discharging tailings waters, illustrating the benefits of innovative hydrometallurgical processes and selectivity research.

A thorough examination of fly ash in some of the most prominent urban waste plants located in Denmark, and using solid waste conversion into electricity, illustrated well the complexity of geochemical multielement partitioning of CRMs and non-CRMs in various types of residues obtained from the combustion process. Although CRMs are not routinely collected in these

industrial sites, the results emphasise the importance of clearly understanding where the CRMs are distributed in any industrial production value chain, since the concentration of these elements may become significant and economic.

Another interesting example of value chain mapping is reported from Iceland and provides evidence that aluminium dross in refineries is devoid of CRMs such as gallium in its waste stream, which reveals the need for careful evaluation of numerous waste products along the value chain of CRMs in aluminium to fully understand how these elements could be partitioned in foundry waste materials.

In summary, the results of these studies confirm the potential for the valorisation of mining and industrial waste, if CRMs are accounted for and effectively do occur in significant amounts. However, there are also numerous barriers that at present prevent the reuse of waste materials, connected with ESG and SLO practices being still in a state of infancy (when dealing with secondary resources) and requiring further development, specifically in the waste valuation and characterisation standards.

[Nordic Database considerations](#)

One objective of this work package (WP2) was to identify and develop workflows that facilitate the archiving of information on secondary resources (mining waste). A workflow that utilises modern data management systems was developed as a trial case (MVP) to help this mapping identification process. Some of the key outcomes firstly concerned a thorough evaluation of the available knowledge on ore deposits and associated waste in the Nordic countries. The areas that were developed involved the interconnection of mineral resource data with geochemical data obtained from direct sampling of secondary resources. What emerged from the experimental work was the need to establish rigorous systems that allow inference, based on this important connection between primary and secondary mineral resources. In other words, ore and waste need to be kept in separate tables in a database, but it is important to maintain a relational link between them to support inferences. In addition, relationships with geochemical samples and the NSCRMD table should be used to facilitate data validation and for informative purposes.

Databases are often complex systems that are difficult to manage and access because of (a) large volumes of data, (b) complex schema, (c) query complexity and (d) data quality (Hariri et al. 2019). The development and use of the ND-MVP provided plausible solutions to facilitate access to both primary and secondary mineral resource data, mitigating some of the issues mentioned.

Informatisation and cloud computing are essential to increase the data processing capacity and knowledge extraction. Section 4.1 provides an example of the SQL processing capacity. The utilisation of Adminer in the proposed solution (ND, MVP) demonstrated the advantage of this solution for complex query development. SQL structured queries and heuristic methods were used to identify sites with a significant CRM potential, highlighting the importance of systematic data filtering and the use of relational database capabilities for effective resource evaluation.

The MVP was also tested to evaluate its capacity to produce consistent results, simulating user interactions with Adminer to perform a comprehensive analysis of historical mining projects. The results obtained highlighted the importance of considering ore genetic types, SR_EI scores and mined tonnage to evaluate the mineral resource potential.

For REE re-mining, Grängesberg provided the most promising project among the closed mines due to its mined tonnage and SR_EI score, coupled with relatively well understood mineral processing requirements. For copper, Løkken could be an economically viable case, given the volumes of waste and presence of Co together with other CRMs. In terms of nickel and PGEs, Hitura presents an attractive option due to its magmatic genetic type and moderate processing complexity if compared to other ore styles (cf. analyses in section 4.1 and 4.2, illustrating the prioritisation based on CRMs, and the estimated waste values, Fig. 4.9). Finally, for cobalt, Løkken stands out again as the most interesting project.

These assessments developed using the ND-MVP provided a clear framework for prioritising historical mining projects based on their CRM potential (Annex D) and economic feasibility, with particular emphasis on projects offering multiple valuable CRMs (Fig. 5.2, CRM_rep). The results of these database studies are compatible with the direct investigations reported in section 3.

The screenshot displays the Adminer web interface for a database. At the top, there are tabs for 'Select data', 'Show structure', 'Alter table', and 'New item'. The 'Select data' tab is active, showing a 'Select' dropdown menu with various fields like Name, Latitude, Longitude, Mined_Mt, Size_category, Status, Country, SR_EI_score, CRM_rep, Genetic_type, and nscrm_nodd_idx. A 'Search' section contains a table with filters: Mined_Mt (IS NOT NULL), Country (LIKE %%), Status (IS), Mined_Mt (>= 0.15), and (anywhere) (=). A 'Sort' section shows 'Mined_Mt' selected with 'descending' order. 'Limit' is set to 50 and 'Text length' to 100. An 'Action' button is also present.

Below the search section, the SQL query is displayed:


```
SELECT "Name", "Latitude", "Longitude", "Mined_Mt", "Size_category", "Status", "Country", "SR_EI_score", "CRM_rep", "Genetic_type", "nscrm_nodd_idx" FROM "nodd_class10052024v1" WHERE "Mined_Mt" >= 0.15 AND "Status" != 'Active mine' AND "Mined_Mt" >= 0.15 ORDER BY "Mined_Mt" DESC LIMIT 50
```

The main part of the interface shows a table with 12 columns: Name, Latitude, Longitude, Mined_Mt, Size_category, Status, Country, SR_EI_score, CRM_rep, Genetic_type, and nscrm_nodd_idx. The table lists various mining projects, including Otanmäki, Outokumpu, Vihanti Zn, Hitura, Mustavaara, Kotalahti, Rautuvaara Mine, Vammala, Hammasahti, Luikonlahti, Laukunkangas, Kyliähti, Pahtavaara Au, Vuonos Cu, Vuonos Ni, Raajärvi, Hannukainen, Laivakangas, Hällinmäki, Ylöjärvi, Kutemajärvi, Saattopora Au, Jussarö, Haveri, Metsämonttu, and Vuorokas. Each row contains data for these fields, such as coordinates, mined tonnage, status, and genetic type.

At the bottom, there are buttons for 'Whole result' (41 rows), 'Modify', 'Selected' (0), and 'Export' (41).

Figure 5.2. Example of the selection query building process in Adminer. Filtering permits the identification of sites with a variable SR_EI_score and CRM_rep occurrence (e.g., see Finnish case studies discussed in section 3.2).

Some of the outlined advantages in terms of classification are also supported by various (non-Nordic) studies on the exploration and extraction of, for instance, platinum group elements (PGEs). Ore deposit studies at the (numerous) Sudbury Cu–(Ni)–PGE systems in Canada (Farrow et al. 2005) illustrate how the refining of classification schemes can enhance the understanding and exploitation of polymetallic deposits of this type, which contain some of the most valuable CRMs. In this case, PGEs are a particularly important example, since they are reasonably understood and often primary production metals and CRMs (a wealth of mineral resources data and paragenetic studies are thus available, illustrating the mineralogical deportment of PGEs). Refining a classification involves detailed analysis and categorisation of the ore types and mineral compositions within a deposit, providing a more precise definition of extraction processes and optimisation of metallurgical techniques (Farrow et al. 2005).

Use of the ND-MVP showed that although the SQL data extractions cannot reveal the mineralogical associations of specific CRMs, they can be useful to rapidly evaluate opportunities based on available information connected to metal or mineral budgets and ore genetic constraints (section 4.1). In other words, preliminary appraisals would be possible and provide initial guidance on evaluation of the waste potential.

Data extraction/filtering using the ND-MVP showed that inferences are possible about the distribution of CRMs that could be either concentrated in specific minerals or dispersed in numerous phases, rendering the metallurgical processes more expensive and thus less economic (section 4.1). The inferences are mostly derived from existing knowledge about metallurgical processing of different styles of mineralisation. For instance, it was possible to compare opportunities for the extraction of REEs in carbonatite complexes vs apatite-rich IOA systems, with the former expected to be less economically viable given the higher mineralogical complexity and relative mineralogical diversity (deportment) of REEs (Fig. 5.3).

	Name	Latitude	Longitude	Mined_Mt	Size_category	Status	Country	SR_EI_score	CRM_rep	Genetic_type	nscrm_nodd_idx
☐	Kirunaavaara	67.83279129	20.19019548	1175.137631	Very large	Active mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	B926
☐	Malmberget	67.18494916	20.6727805	632.375591	Very large	Active mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1258
☐	Sillinjärvi	63.116362	27.735605	294.197474	Large	Active mine	Finland	75.075	F, REE, P	Carbonatite associated (Cu, Fe, Ti, V, Nb-Ta, REE, U)	BF306
☐	Grängesberg	60.08285836	14.996639	132.781542	Large	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF996
☐	Leveäniemi	67.63331834	21.02615096	89.319397	Large	Active mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1299
☐	Tuolluvaara	67.85352541	20.31982406	25.00015	Medium	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1265
☐	Luossavaara	67.87328008	20.22163663	21.156932	Medium	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1264
☐	Risbäcksfältet	60.08668351	14.99834627	20.363143	Medium	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF997
☐	Blötbergsfältet	60.12418297	15.08018932	15.769534	Medium	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	B779
☐	Rautuvaara Mine	67.49992	23.93583	11.564	Medium	Closed mine	Finland	40.725	Cu, REE	Iron oxide-copper-gold	B010
☐	Gruvberget	67.64522983	20.99098217	11.054048	Large	Closed mine	Sweden	231.42	V, Ti, P, REE	Apatite iron ore	BF1300
☐	Idkerbergsfältet	60.378357	15.22849326	11.044126	Small	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	B728
☐	Nukutus	67.89695955	20.25954098	5.338281	Small	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1266
☐	Hannukainen	67.55461	23.97931	4.563	Large	Closed mine	Finland	115.705	Cu, {Co}, REE	Iron oxide-copper-gold	BF036
☐	Lekombergsfältet	60.20653434	15.13967261	2.806796	Small	Closed mine	Sweden	231.42	V, Ti, P, REE	Apatite iron ore	B783
☐	Haukivaara	67.86599876	20.24170978	2.359636	Small	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF1263
☐	Örnsbergsfältet	60.07651856	14.98781645	2.299269	Small	Closed mine	Sweden	231.42	V, Ti, P, REE	Apatite iron ore	BF998
☐	Mertainen	67.70579522	20.77943752	1.682994	Large	Active mine	Sweden	231.42	V, Ti, P, REE	Apatite iron ore	BF1301
☐	Klacks-Lerberg	59.59869766	14.92228769	1.329816	Small	Closed mine	Sweden	633.535	Mn, Ni, V, Ti, Co, P, REE	NULL	BF867
☐	Seve	59.281214	9.282014	1.15	Small	Closed mine	Norway	371.7	Ta, REE, Ti, Nb, V	Carbonatite associated (Cu, Fe, Ti, V, Nb-Ta, REE, U)	B135
☐	Søftestad	59.151244	8.515313	0.87	Small	Closed mine	Norway	633.535	Mn, Ni, V, Ti, Co, P, REE, F	NULL	BF613
☐	Korsnäs	62.812874	21.239443	0.869	Small	Closed mine	Finland	138.395	Cu, Nb, REE	Carbonatite associated (Cu, Fe, Ti, V, Nb-Ta, REE, U)	B045
☐	Fredmundbergsfältet	60.13416341	15.09976297	0.793633	Small	Closed mine	Sweden	343.68	{Mn}, V, Ti, P, REE	Apatite iron ore	BF989
☐	Lombsfältet	60.06300383	14.97918148	0.606894	Small	Closed mine	Sweden	231.42	V, Ti, P, REE	Apatite iron ore	B800

Figure 5.3. Adminer SQL search output that targets REE opportunities. The filtering permits the identification of sites with a variable SR_EI_score and CRM_rep occurrence.

Another essential objective of this project was to develop methods that help with evaluation of the critical raw material (CRM) potential by suggesting possible classification strategies. The approaches were expected to be consistent with what is already utilised for primary mineral resources.

Mineral resources and waste classification is a complex problem. This is due to the limited data on resources, particularly mining waste (Kinnunen & Kaksonen 2019, Kinnunen et al. 2022), and on by-products (CRMs) in primary ores (McNulty & Jowitt 2021). Mining companies in fact have no formal requirement to report or quantify the abundance of CRMs in their concentrates and stockpiles of primary and secondary ore/waste, unless these are primary production metals.

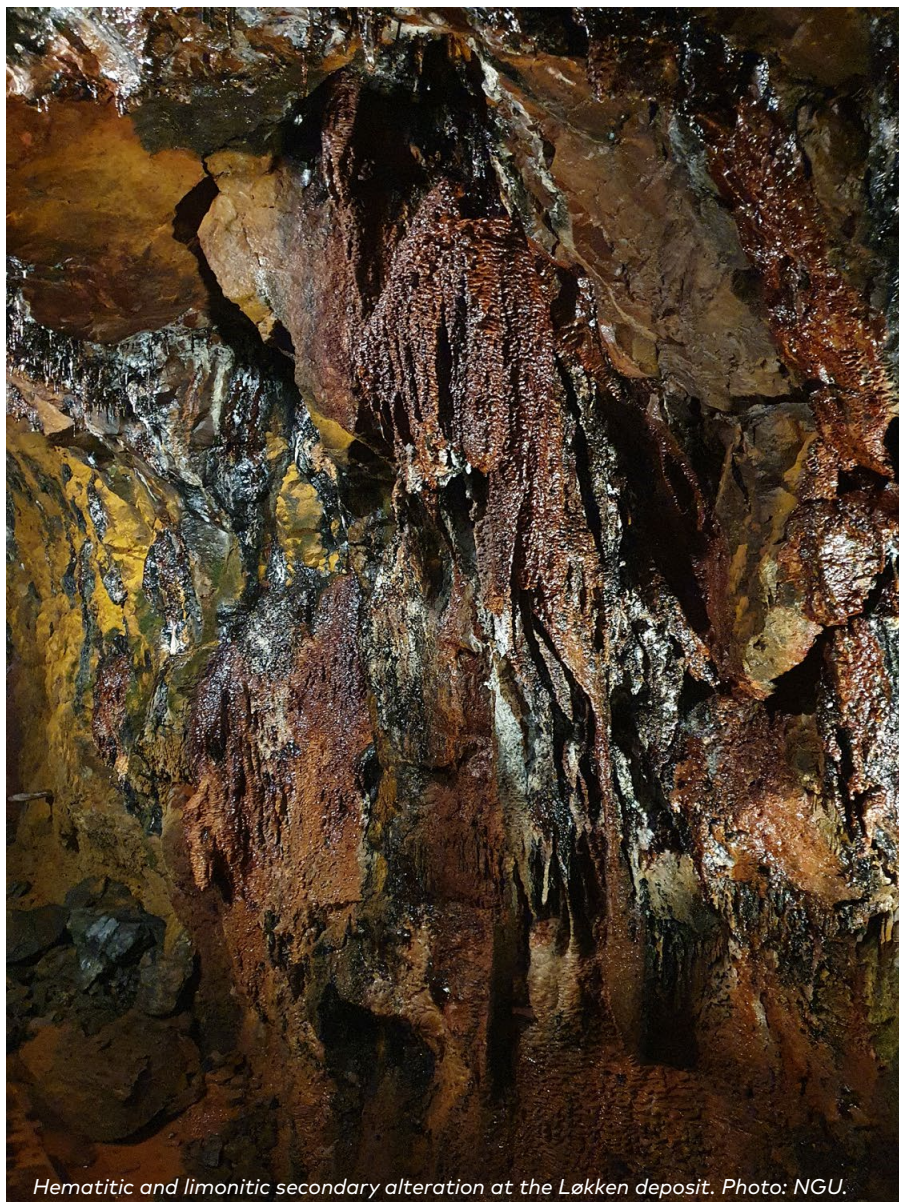
Despite the challenges, numerical and statistical inference and predictive analysis, for instance, to estimate the mass and grade of CRMs in secondary resources, are plausible solutions to at least partly resolve these limitations, especially if the estimation of these resources is carried out in initial evaluations of historical mining sites or in undiscovered mineral resource assessments. These inferences can provide useful information, as presented in section 4.1 and proposed in the literature (Werner et al. 2015, Mudd & Jowitt 2018, Bertelli & Feltrin 2023, Feltrin & Bertelli 2023).

Instead of exclusively considering the mineral resource data, assessments can also be developed by considering data that directly represent criticality scores (McNulty & Jowitt 2021). Knowledge concerning primary resources such as metal associations and the application of companionality and ore genesis concepts to infer the occurrence of CRMs represent new potential methodologies to compare historical projects while considering their overall potential. The introduction of new scoring systems (e.g., the SR_EI score, section 4.1) provides additional guidance on the classification of ores and associated waste (CRM_rep, Fig. 5.3, for instance predictions showing variable polymetallic associations in ore systems of the equal genetic style). In this project, it was important to realise that CRM classifications (EU Commission 2023a) can be integrated with mineral resource databases to produce more advanced classification systems offering a higher degree of discrimination and predictivity, resulting in more informed approaches to the valorisation of mining waste.

Another approach to the classification of resources is to use *in situ* value calculations (section 4.2). The economic valuation methodologies, including metal-equivalent calculations and NSR models, offered a practical approach to the development of estimates of the potential value of CRMs in mining waste. This approach helps prioritise sites for further exploration and potential exploitation; however, they can also help with preliminary appraisals of mining waste, especially if detailed geochemical characterisation of the waste is available (e.g., Juutinen et al. 2023). These crude calculations, as seen earlier in the discussion on the global classification of mafic-to-ultramafic Ni–Cu–PGE deposits (Peck & Huminicki 2016), expand the variety of prospective deposit styles, since CRMs add to the overall equivalent *in situ* resources. The use of metal or grade equivalents is then more inclusive and can reveal previously unnoticed historical projects in the context of both primary and secondary ore/waste. Because of the more inclusive estimates, historical polymetallic projects with significant waste could become economic to mine (under favourable commodity pricing conditions, assuming that PGEs and Ni–Cu sulphide ores are recoverable).

The results of the application of metal equivalents illustrate how their calculation can be "tuned" to evaluate the effect of commodity prices, but most importantly they can provide value estimates of by-products, which in some cases can represent significant added value to a mining operation (e.g., Downie 2019).

In conclusion, the project demonstrated possible solutions for the inventorying and classification of mining waste and highlighted the need for more advanced geoinformation tools capable of integrating data at different scales of analysis and connecting them across multiple disciplines, such as criticality studies and economic valuations. These findings reconnect with earlier considerations of the benefit of more complex numerical characterisations of ores (NSR models) (Goldie & Tredger 1991). By embedding more of the economic aspects of ore deposit mining, an economic geologist would be forced to understand (for instance) the metallurgical implications and the effect of other "out of the mine" costs that impact project economics.



Hematitic and limonitic secondary alteration at the Løkken deposit. Photo: NGU.

6 Recommendations

A series of recommendations and possible future developments are briefly outlined for improvement of the circularity action and to increase understanding of the supply potential of raw materials for the green transition:

Recommendations connected with the case studies

One important distinction to make between primary ores and mining waste is the degree of knowledge available to a decision maker. The valuation of secondary resources, especially with respect to the definition of their mass, is much simpler. Many ore deposits will be harder to define in the sense that their extent may be difficult to ascertain and often remains untested (e.g., the Kemi deposit in Finland is still open at depth). Studies that characterise the waste mass and composition are essential to obtain correct interpretations and estimations of the mineral potential (as illustrated in section 3) and would return accurate estimates, given the finite dimensions of waste materials.

Despite this, and in the context of evaluating the feasibility of a project, it is necessary to study several factors outside the economics of a resource, the *in situ* value. For instance, it is understood that projects involving the recovery of waste in active mines that have primary ongoing production or are in the closure stage, e.g., Pyhäsalmi re-mining of Fe and S from tailings (Figueiredo et al. 2019), are more likely to become recycling and re-mining operations. Similarly, operations that would restart with plans for primary production of ores that also include the recovery of waste would be preferable (e.g., Otanmäki). This is because the economics of waste are likely to be poor and the by-product potential is often negligible if compared with the mined value of primary resources. This would imply that studies evaluating a specific waste accumulation should also consider the infrastructure already available, as well as up-to-date mineral resource estimates of primary ores yet to be mined.

Implementing sustainable CRM recovery practices from mining waste can significantly contribute to the circular economy. This requires collaboration between governmental agencies, industry stakeholders and research institutions to develop and apply best practices. Environmental and social governance (ESG) considerations are also integral to the assessment process, ensuring that CRM recovery plans align with sustainable development goals and community expectations (section 3, Finnish case studies).

Policymakers should leverage the insights from this report to formulate strategies that support the sustainable extraction and use of CRMs. This includes creating incentives for re-mining projects, ensuring compliance with ESG standards and fostering innovation in CRM recovery technologies. Finally, legislation should consider in more detail the problem of quantification and qualitative descriptive representation of secondary resources to obtain standards and codes of practice for the mining industry, comparable to EU standards on company reporting for primary resources (e.g., PERC, UNFC).

Recommendations connected with the Nordic Database

The experience of constructing a resource in the cloud containing data on mining waste illustrates the advantage of using modern computational systems to share geoinformation. Much more can still be done in terms of automating data processing to extract knowledge from legacy data. An untapped area concerns the design of tools that connect more tightly with existing services in the cloud. Financial technology systems that provide real-time pricing of commodities could be a possible extension, supporting a higher level of automation providing comprehensive multidisciplinary evaluations of ore deposits and their associated waste products.

Thus, an important recommendation is to look outside the realm of geological information, expanding the types of data that are considered in ore and waste valuations. Continued development and refinement of the integrated database are crucial for maintaining up-to-date information on the CRM potential. This includes regular updates and the incorporation of new data sources as they become available.

Further development of the resource (ND-MVP) would require improvement of the classification systems adopted with a tighter integration of the criticality and economic based valuations of primary ore deposits and waste. This would require further workflow and automation developments to test, for instance, new classification algorithms.

Thus, the recommendation is to explore and better understand numerical and statistical workflows contributing to improved classifications of natural resources (these systems may consider conventional statistical approaches or even machine learning tools).

With respect to such processing and if the scope is directed at developing numerical inferences, it would be significant to include or connect Nordic country data with other global resources databases on ore deposits, especially databases containing mineral resource estimates on CRMs (Feltrin & Bertelli 2023). The recommendation is then to increase the scale of integration.

As a summary of the recommendations discussed, future developments should focus on refining CRM recovery technologies (section 3.5), enhancing the capabilities for data analytics (section 4) and exploring new sources of CRMs (section 3). Additionally, pilot projects should be undertaken to test the feasibility of large-scale CRM recovery from mining waste. By addressing these key areas (including ESG and SLO; section 3.1), the Nordic countries can enhance their CRM supply security, contribute to global sustainable development and support the green energy transition.

Annexes

Annex A

Three algorithms were developed to establish a relationship between the two tables hosting the data (NODD, NSCRMD) using the R statistical language. Two algorithms respectively performed resource name matching using Jaccard distance analysis and nearest neighbour analysis to pair locations using their geographic coordinates.

The third algorithm compiles an entirely new field in the NSCRMD table with the inferred CRMs based on a set of rules considering companionship and ore genesis concepts.

P1: Pseudocode implemented in R to process the data. Nearest neighbour analysis

```
1. // Import necessary libraries
2. IMPORT sf
3. IMPORT dplyr
4. IMPORT writexl
5.
6. // Assuming dfa1 and dfa2 are your datasets
7. SET dfa1 TO summary_stats5_wgs84
8. SET dfa2 TO NODD2022_1_1_ORIGINAL
9.
10. // Convert datasets to spatial (sf) objects with specified coordinates and CRS
11. CONVERT dfa1 TO sf OBJECT sf1 WITH lon, lat, CRS 4326
12. CONVERT dfa2 TO sf OBJECT sf2 WITH Longitude, Latitude, CRS 4326
13.
14. // Add an ID field to sf1 and sf2
15. ADD ID field to sf1: "A" + row_number
16. ADD ID field to sf2: "B" + row_number
17. ADD Name field to sf1 from sf1$AREA.LOCALITY
18.
19. // Compute distances between all points in sf1 and sf2
20. COMPUTE distances between sf1 and sf2
21.
22. // Create an empty dataframe for results
23. INITIALIZE empty dataframe result with columns: Name_nodd, Name_sw, ID1, ID2,
Distance
24.
25. // Iterate over each point in sf1
26. FOR EACH point in sf1:
27.     FIND nearest neighbor in sf2 within 5 km
28.     IF nearest neighbor distance <= 5 km:
29.         ADD row to result with names, IDs, and distance
30.
31. // Convert sf1 and sf2 back to dataframes
32. CONVERT sf1 TO dataframe df1
33. CONVERT sf2 TO dataframe df2
34.
35. // Join results to df1 and df2
36. JOIN result to df1 on ID1
37. JOIN result to df2 on ID2
38.
39. // Rename and reorder columns in df1 and df2
40. RENAME and REORDER columns in df1 and df2 for associated IDs and names
41.
42. // Remove duplicate rows from df1 based on all columns except the first
```

```

43. REMOVE duplicate rows from df1
44.
45. // Write updated df1 and df2 to Excel files
46. WRITE df1r to Excel file "summarystats5_NSCRM2023June_v1_03062023_wasteon-
ly_cleaned_wgs84.xlsx"
47. WRITE df2 to Excel file
"NODD2022_1_1_ORIGINAL_v1_03062023_wasteonly_cleaned_wgs84.xlsx"
48.

```

P2: Pseudocode implemented in R to process the data. Name matching.

```

1. // Import necessary libraries
2. IMPORT readxl
3. IMPORT textTinyR
5. // Load data from Excel files
6. LOAD DATA from "NODD2022_2_LF_uniq_names.xlsx" into NODD2022_1_1_ORIGINAL
8. // Install the textTinyR package if it's not already installed
9. CHECK IF textTinyR is installed
10. IF NOT, INSTALL textTinyR
12. // Load the textTinyR library
13. USE textTinyR library
15. // Define two vectors of names from the datasets
16. SET names1 TO NODD2022_1_1_ORIGINAL$Name
17. SET names2 TO merged_array
19. // Define a function to calculate Jaccard similarity between two strings
20. DEFINE FUNCTION jaccard(a, b):
21.   CONVERT a and b to lowercase
22.   SPLIT a and b into unique characters
23.   CALCULATE intersection and union of characters
24.   RETURN intersection divided by union
25.
26. // Create a data frame with all combinations of names from names1 and names2
27. CREATE DATAFRAME df from combinations of names1 and names2
28.
29. // Calculate Jaccard similarity for each combination
30. APPLY jaccard function to each combination in df
31.
32. // Filter combinations with Jaccard similarity above 0.85
33. FILTER df for similarities >= 0.85, CONVERT to percentage, and REMOVE duplicates
34.
35. // Create new dataframes df_names1 and df_names2
36. INITIALIZE df_names1 with names1 and empty df2_ID
37. INITIALIZE df_names2 with names2 and empty df2_ID
38.
39. // Find and assign matching IDs from df2 to df_names1 and df_names2
40. FIND matching indices for names in df2
41. ASSIGN df2_IDs to df_names1 and df_names2 based on these indices
42. KEEP only complete cases in df_names1 and df_names2
43.
44. // Print the updated dataframes
45. PRINT df_names1
46. PRINT df_names2
47.
48. // Add the ID field to original dataframes from df_names1 and df_names2
49. JOIN NODD2022_1_1_ORIGINAL with df_names1
50. JOIN summary_stats5_wgs84 with df_names2
51.
52. // Reorder columns and create complete cases
53. REORDER columns in NODD2022_1_1_ORIGINAL and summary_stats5_wgs84 to bring df2_ID
to the front
54. CREATE complete case of NODD2022_1_1_ORIGINAL with df2_ID
55.

```

```

56. // Add corresponding 'Name' values from NODD2022_1_1_DF2MATCH to summary_stats5_wgs84
57. JOIN summary_stats5_wgs84 with NODD2022_1_1_DF2MATCH on df2_ID
58.
59. // Rename and relocate the 'Name' field in summary_stats5_wgs84
60. RENAME 'Name' to 'Name_Similarity' in summary_stats5_wgs84
61. RELOCATE 'Name_Similarity' after 'METHOD' field
62.
63. // Write the updated dataframes to Excel files
64. WRITE summary_stats5_wgs84 TO "summarystats5_NSCRMD_2023June_v1_03062023_wasteonly_
cleaned_wgs84.xlsx"
65. WRITE NODD2022_1_1_ORIGINAL TO "NODDMOD5_NSCRMD_2023June_v1_03062023_wasteonly_
cleaned_wgs84.xlsx"
66.

```

P3: Pseudocode implemented in R to process the data. CRM companionship analysis and attribution.

```

1. // Import necessary libraries
2. IMPORT dplyr
3. IMPORT purrr
4. IMPORT stringr
5. IMPORT readxl
6. IMPORT writexl
7.
8. // Define a dictionary as a dataframe
9. CREATE DATAFRAME dict_df WITH COLUMNS:
10.   - element: ["Au", "Al", "Ti", "Fe", "Ni", "Cu", "Zn", "Pb", "Sn", "Pt", "U"]
11.   - string: Corresponding string values for each element
12.
13. // Read data from an Excel file
14. READ EXCEL FILE "Merged_Table20062023_impLFedits.xlsx" INTO Merged_Table20062023_
impLFedits
15.
16. // Extract the 'Main_Commodity...90' column from the read data
17. SET chem_vector TO Merged_Table20062023_impLFedits$Main_Commodity...90
18.
19. // Define a function to map elements to strings
20. DEFINE FUNCTION element_to_string(element):
21.   IF element is in dict_df$element
22.     RETURN corresponding string from dict_df
23.   ELSE
24.     RETURN empty string
25.
26. // Apply the mapping function to each element in chem_vector
27. SET mapped_vector TO MAP each element in chem_vector:
28.   SPLIT chem_str by comma, TRIM spaces
29.   MAP each chem_element to element_to_string
30.   COMBINE the results into a string, REMOVE duplicates, NA, and empty strings
31.   RETURN the combined string
32.
33. // Combine chem_vector and mapped_vector into a new dataframe
34. CREATE DATAFRAME result_df WITH COLUMNS:
35.   - original: chem_vector
36.   - mapped: unlist(mapped_vector)
37.
38. // Write the result dataframe to an Excel file
39. WRITE result_df TO EXCEL FILE "result_df.xlsx"
40.

```

Annex B

Examples of metal equivalent calculations carried out for some of the major deposits in the Nordic countries. The calculations consider different pricing models to illustrate the variation in estimates of CuEq tonnes (section 4.2).

ID_Nat	Name	Lat	Lon	Main Metals	Other Metals	Combined Resources (Mt)	Metal Factors (CuEq 100,000 t, 2013-2022)	Metal Factors (CuEq 100,000 t, Q4 2023)	Equation 1: metal pricing avg 2013-2022 (100,000 tonnes of CuEq) (*)	EqCu t (2013-2022)	Equation 2: last quarter of 2023 (100,000 tonnes of CuEq) (**)	EqCu t (Q4 2023)
F0165	Talvivaara	64,0	28,1	Ni,Zn	Cu, Co, U, Mn, Ag, PGE	1395,881	Cu: 1000000, Zn: 268358, Pb: 328936, Au: 15, Ag: 1100, Ni: 45904, Co: 16485	Cu: 1000000, Zn: 288072, Pb: 407552, Au: 12, Ag: 835, Ni: 50634, Co: 22385	Calculation 1(a), listed in footnote.(**)	16 203 127	Calculation 11(a), listed in footnote.(**)	14 820 412
S0869	Kirunavaara	67,8	20,2	Fe	P, Mn	794	Fe: 7300155, Mn: 1260465, P: 2814725	Fe: 7016807, Mn: 16660634, P: 3360161	Calculation 2(b)	19 781 857	Calculation 12(b)	20 425 193
F0180	Kemi	65,8	24,7	Cr		130,900	Cr: 234291	Cr: 210646	Calculation 3(c)	18 874 200	Calculation 13(c)	20 992 846
S0861	Malmberget	67,2	20,7	Fe, Mn, P		1093,4	Fe: 7300155, Mn: 1260465, P: 2814725	Fe: 7016807, Mn: 16660634, P: 3360161	Calculation 4(d)	13 278 764	Calculation 14(d)	13 386 715
S0840	Aitik	67,1	21,0	Cu, Au		1147	Cu: 1000000, Zn: 268358, Pb: 328936, Au: 15, Ag: 1100	Cu: 1000000, Zn: 288072, Pb: 407552, Au: 12, Ag: 835	Calculation 5(e)	10 963 690	Calculation 15(e)	11 753 504
N0188	Tellnes	58,3	6,4	Ti	Fe, Ni	575	Fe: 7300155, Ti: 1805988	Fe: 7016807, Ti: 2180157	Calculation 6(f)	4 359 483	Calculation 16(f)	3 631 617
N0192	Ørtrfjell	66,4	14,7	Fe		338,9	Fe: 7300155	Fe: 7016807	Calculation 7(g)	1 940 753	Calculation 17(g)	2 019 124
N0098	Bjørnevatn	69,7	30,0	Fe		146,6	Fe: 7300155	Fe: 7016807	Calculation 8(h)	1 873 494	Calculation 18(h)	1 949 149
F0352	Sililinjärvi	63,1	27,7	P		2964,3	P: 2814725	P: 3360161	Calculation 9(i)	1 818 787	Calculation 19(i)	1 523 554
S0906	Gruvberget	67,6	21,0	Fe	P	399	Fe: 7300155	Fe: 7016807	Calculation 10(l)	1 817 240	Calculation 20(l)	1 890 623

Detailed Calculation List

(*)Equation 1, Talvivaara example: ((Cu(t) / MFCu) + (Zn(t) / MFCZn) + (Pb(t) / MFPPb) + (Ag(t) / MFAg) + ((Ni(t) / MFNi) + ((Co(t) / MFCo) * 100,000 t = 16.20 Mt CuEq.

** (a) Calculation 1: ((2224600/100000)+(8262800/268358)+(79450/328936)+(4290/1100)+(3972500/45904)+(301910/16485))*100000

(b) Calculation 2: ((1432340780/7300155)+(2031455/1260465))*1000000

(c) Calculation 3: (44220551/234291)*1000000

(d) Calculation 4: ((920546909/7300155)+(4841469/1260465)+(8013466/2814725))*1000000

(e) Calculation 5: ((7317744/100000)+(257724/268358)+(898393/328936)+(425/15)+(4878/1100))*1000000

(f) Calculation 6: ((7000000/7300155)+(77000000/1805988))*1000000

(g) Calculation 7: (141678000/7300155)*1000000

(h) Calculation 8: (136768000/7300155)*1000000

(i) Calculation 9: (51193863/2814725)*1000000

(l) Calculation 10: (132661336/7300155)*1000000

** (a) Calculation 11: ((2224600/100000)+(8262800/288072)+(79450/407552)+(4290/835)+(3972500/50634)+(301910/22385))*1000000

(b) Calculation 12: ((1432340780/7016807)+(2031455/16660634))*1000000

(c) Calculation 13: (44220551/210646)*1000000

(d) Calculation 14: ((920546909/7016807)+(4841469/16660634)+(8013466/3360161))*1000000

(e) Calculation 15: ((7317744/100000)+(257724/288072)+(898393/407552)+(425/12)+(4878/835))*1000000

(f) Calculation 16: ((7000000/7016807)+(77000000/2180157))*1000000

(g) Calculation 17: (141678000/7016807)*1000000

(h) Calculation 18: (136768000/7016807)*1000000

(i) Calculation 19: (51193863/3360161)*1000000

(l) Calculation 20: (132661336/7016807)*1000000

Annex C

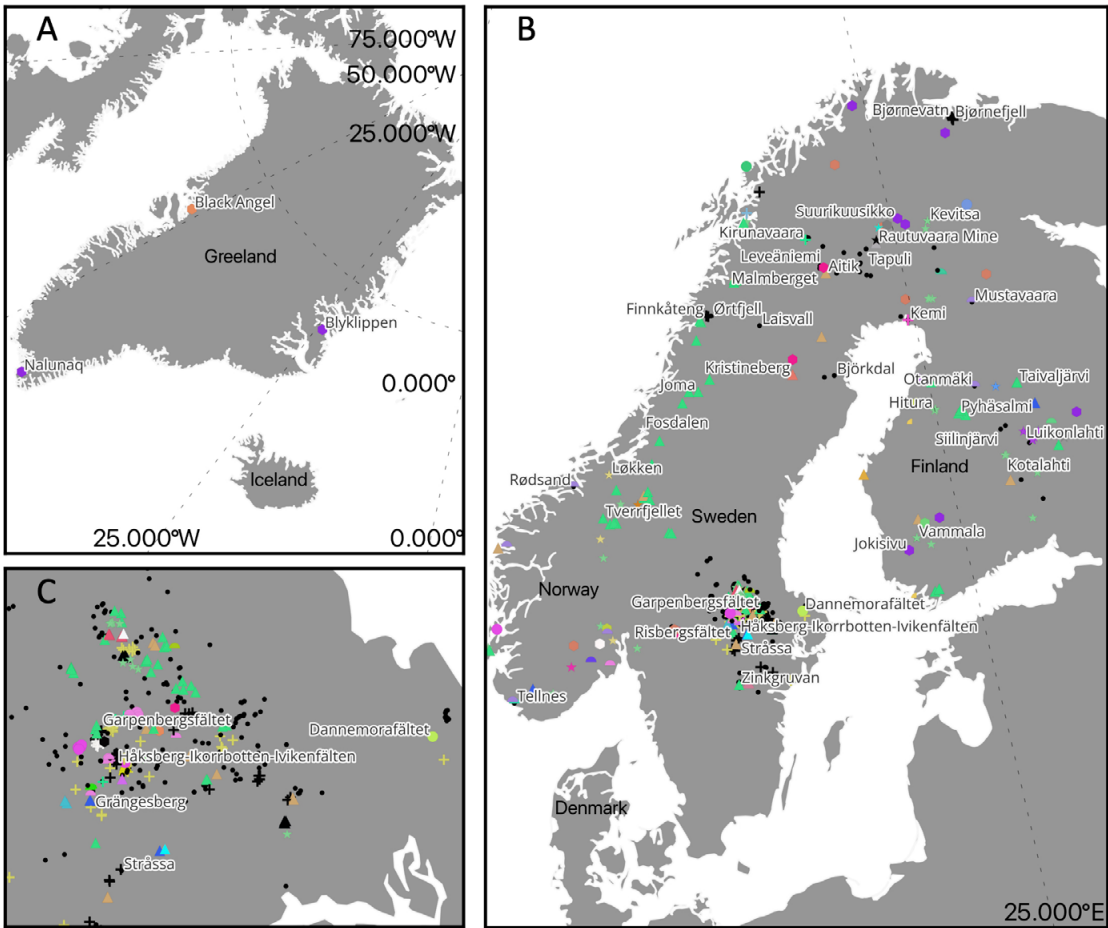
Summary of calculated metal tonnes of selected Finnish deposits with reported tailings data on tonnages and grades. Table sorted according to estimated (non-compliant) value in USD.

Site Main Locality	Latitude	Longitude	Main Commodity	Country	CuEq mt	Value USD	Tailings (t)
kemi	65,78	24,71	Cr	Finland	395 812	\$2 638 875 613	13 000 000
hitura	63,85	25,05	Ni, Cu	Finland	112 219	\$748 161 716	15 000 000
pyhäsalmi	63,66	26,05	Cu, Zn, Au	Finland	75 299	\$502 019 665	16 000 000
keivitsa	67,70	26,97	Ni, Cu, PGE	Finland	73 099	\$487 350 198	10 020 000
luikonlahti	62,94	28,70	Co,Cu,Ni	Finland	72 162	\$481 106 731	11 500 000
keretti	62,72	28,99	Cu, Zn, Au, Ag	Finland	60 986	\$406 595 202	10 500 000
vihanti	64,41	25,14	Zn, Cu, Pb	Finland	60 656	\$404 390 860	13 700 000
vuonos	62,76	29,09	Cu, Co, Ni, Zn	Finland	55 397	\$369 328 627	9 100 000
mustavaara	65,81	28,09	V,Fe,Ti	Finland	52 217	\$348 131 545	11 500 000
stormi	61,34	23,04	Ni,Co,Cu	Finland	50 507	\$336 733 218	7 520 000
kotalahti	62,58	27,61	Cu, Ni	Finland	37 494	\$249 975 343	9 400 000
haveri	61,71	23,24	Cu, Au, Fe	Finland	21 811	\$145 416 927	1 400 000
hammaslahti	62,46	30,03	Cu, Zn, Au	Finland	20 416	\$136 110 471	5 300 000
aijala	60,19	23,36	Cu, Zn, Ag	Finland	18 069	\$120 465 290	2 000 000
pahtavaara	67,74	25,73	Au	Finland	13 059	\$87 062 207	5 000 000
virtasalmi	62,06	27,55	Cu, S	Finland	9 401	\$62 675 892	4 150 000
ylöjärvi	61,61	23,50	Cu, W, As	Finland	6 969	\$46 465 143	2 800 000
makola	63,82	24,99	Ni, Cu	Finland	3 452	\$23 017 257	410 000
korsnäs	62,81	21,24	Pb	Finland	714	\$4 757 503	770 000
CRM Metal Tonnes*	Al	As	Ba	Cu	Ga	Mg	Mn
kemi							
hitura				14760		4650000	
pyhäsalmi	448000	6176	1782400	14896	139,2	380800	3760
keivitsa	68937,6	110,9214		8076,12			
luikonlahti	81339,5	749,8		7797		1113809,5	15582,5
keretti	20160	136,5		8200,5		220500	1816,5
vihanti				10960			
vuonos				3185			
mustavaara	316250	34,5	667	8855		136850	5635
stormi		103,024		9039,04		1101680	
kotalahti		28,2		3102		1118600	10340
haveri		221,2		1162			
hammaslahti		530		4028			1616,5
aijala				2400			
pahtavaara	66000	30	1910	400		181000	4950
virtasalmi				850,75			
ylöjärvi				576,8			
makola	6766,64			368,18			173,84
korsnäs							
CRM Metal Tonnes*	Ni	Pd	Pt	Sb	Ti	V	W
kemi	13000						
hitura	32085	1,5	0,75				
pyhäsalmi	464				19200	1136	
keivitsa		23,046		187564,38			413,826
luikonlahti	7716,5						
keretti	3937,5			1050			
vihanti							
vuonos	7007						
mustavaara	954,5			46	28060	5980	
stormi	8888,64			0,752		211,688	
kotalahti	5734						
haveri	110,6					291,2	
hammaslahti	79,5						
aijala							
pahtavaara	1950			1	3800	435	
virtasalmi	415						
ylöjärvi							4480
makola	850,75						
korsnäs							

* Metal and mineral tonnes were estimated based on the mass of waste and available data on elemental concentrations in the tailings. These are only proposed in the metal equivalent calculation to compare deposits it should not be considered a resource estimate of sufficient standard.

Annex D

Mapping of secondary resources in the Nordic countries. A) Projects with historical production of marine tailings and other waste rock accumulations in Greenland. B) CRM metal/mineral associations presented for secondary resources in Norway, Sweden and Finland. C) Enlargement illustrating metal/mineral associations (mapped secondary resources) in the Bergslagen district in Sweden. Deposits with a significant CRM potential in the associated waste are named (see Table 4.4 for further information).



EPSG:5938 (Greenland Polar Stereographic Projection, rotated 45 degrees)

CRM Associations (Estimated)

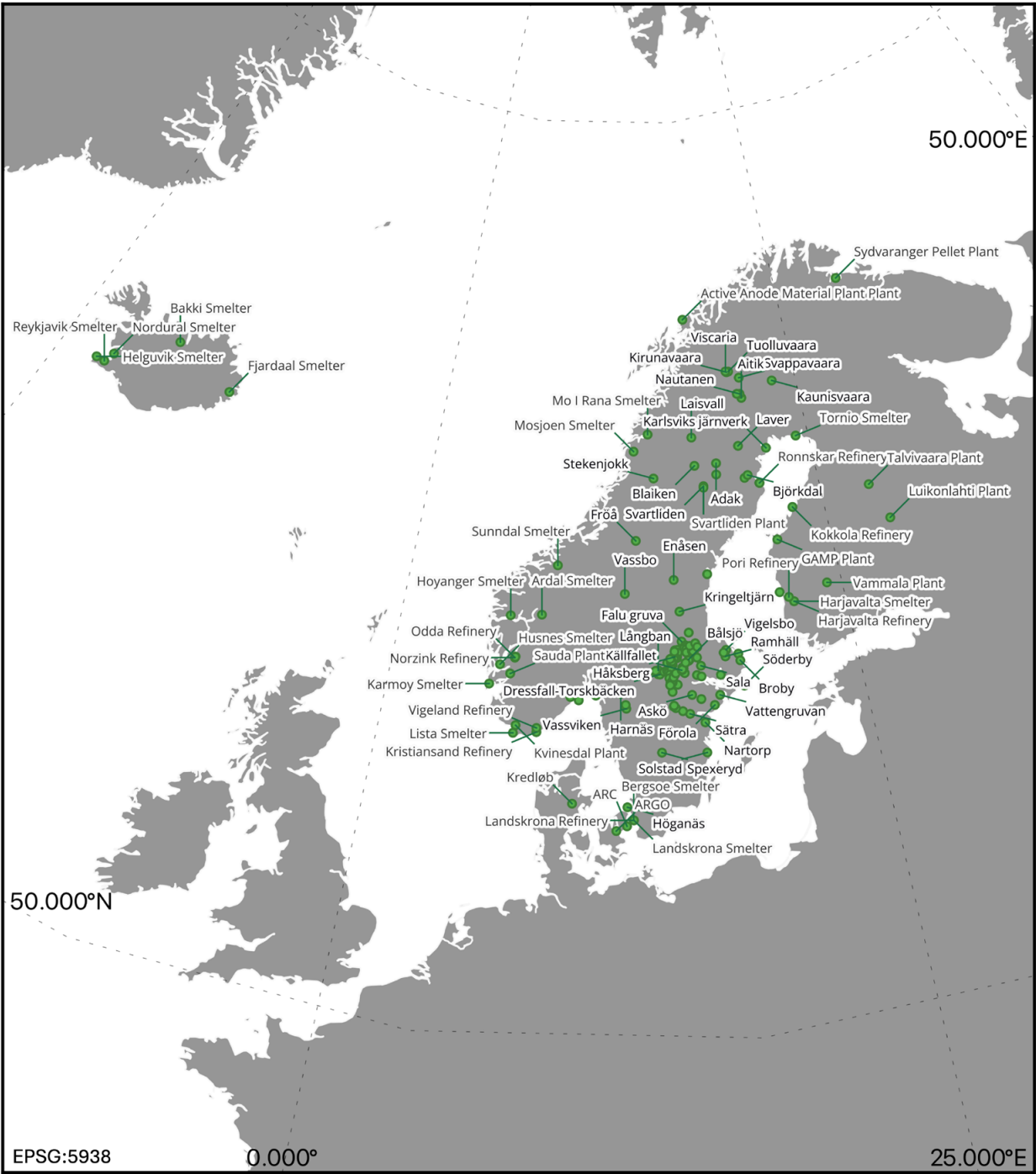
NSCRM DB 11052024 [585]	★ Co,Cu,Ga,Ge,In,Ni,PGE [5]	▲ Cu,In,Mn [1]	+ Mn,P,REE,Ti,V [6]
● As,Bi,Co,Cu,Ge,In,Ni,PGE [2]	★ Co,Cu,Ge,In [2]	▲ Cu,Mn,Ni,Ti,V [1]	● Nb,REE,Ta,Ti,V [1]
● As,Bi,Co,Cu,Ge,In,Ni,PGE,W [1]	★ Co,Cu,Ni,PGE [36]	▲ Cu,Nb,REE [1]	● Ni,Ti,V [1]
● As,Co,Cu [8]	★ Co,Cu,REE [1]	▲ Cu,Ni [2]	● P [2]
● As,Co,Cu,Ge,In,Ni [2]	★ Co,Mn,Ni,P,REE,Ti,V [1]	▲ Cu,REE [1]	● P,REE,Ti,V [18]
● As,Co,Cu,Ge,In,Ni,PGE [11]	★ Co,Gr [1]	● P,REE [1]	● REE [1]
● As,Co,Cu,Ni [1]	★ Co,Mn,Ni,P,REE,Ti,V [1]	● Ga,Ge,In [8]	● Sb,W [1]
● As,Cu [11]	▲ Cu [5]	● Ga,Ge,In,Mn [1]	● Ti,V [6]
● As,Cu,Ga,Ge,In [2]	▲ Cu,Ga,Ge,In [72]	● Gr [1]	● V [2]
● As,Cu,In [3]	▲ Cu,Ga,Ge,In,Mn [15]	● HREE,LREE,Mn,P,V [6]	● W [1]
● Be,Li,Nb,REE,Ta [2]	▲ Cu,Ga,Ge,In,Sb [1]	● Mg,PGE,Ti,V [1]	● Significant Producers
★ Co,Cu [1]	▲ Cu,Ge,In [15]	● Mn [42]	
★ Co,Cu,Ga,Ge,In [6]	▲ Cu,Ge,In,Ni [7]	● Mn,Ni,P,Ti,V [1]	
★ Co,Cu,Ga,Ge,In,Mn,Ni,PGE [1]	▲ Cu,Ge,In,W [2]	● Mn,Ni,Ti,V [49]	
★ Co,Cu,Ga,Ge,In,Ni [1]	▲ Cu,In [12]		

Background

Continents

Annex E

Mapping of facilities that process primary and secondary materials (mainly base and precious metals) in the Nordic countries.



NSCRMD (Smelters, Refineries, Incinerators, Plants and Concentrators)

Facility location

Basemaps

Continents



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