Nordic Innovation

The Nordic Supply Potential
of Critical Metals and Minerals for a Green Energy Transition

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Table of contents


Kevitsa nickel mine, Finland. Photo J.Brusila.

Executive summary

The transformation of the current 'high-carbon emission' into a 'low-carbon emission' society is an essential part of climate change mitigation. At the core of this is what can be called a '**Green Energy Transition**', an over-arching ***transition from non-renewables to renewables-based production, storage, transmission and use of energy***. This is a major technological change that includes significantly increasing demand for raw materials of all kinds (Figure A), which, combined with the general technological development of society and industry, have already resulted in many globally major economic players, such as the EU, to define sets of mineral-based raw materials as critical (CRM). A raw material is deemed 'critical' if it is of high importance to the economy and if its supply is associated with a high risk of disruption. An absolute majority of the present critical raw materials are metals which are sourced from geological occurrences through mining.

Secure and resilient supply chains of the CRMs are essential for the economic security of any industrialised country or larger economic entity, the Nordic region included. In this context, we provide a review of production, and known and assumed resources of the CRMs in the Nordic countries, both in local and global perspectives, indicate major data and information gaps, and suggest lines of full-scale research to immediately follow.

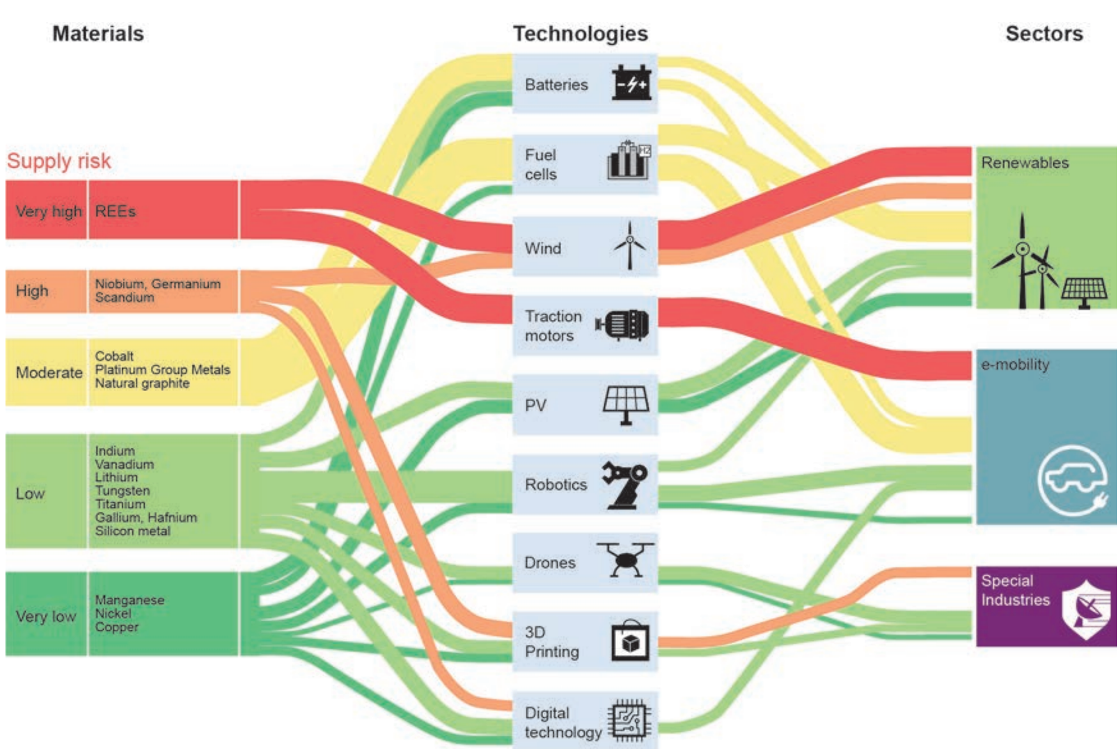

Figure A. Raw materials needed for the green energy transition and their supply risks, as defined in the latest CRM review for the European Union (2020). REEs = rare earth elements; Platinum Group = platinum-group metals (PGM; mainly platinum and palladium).

The data produced from this research, including their incorporation in a suggested new Nordic deposit database, will provide vital tools for decision-makers, as well as offer direct information and guidelines for the society, industry, and academia.

Overall, we find the Nordic supply potential for the CRMs to be relatively large, but with substantial variations, both regarding geological favourability within and between the countries, and in the state of knowledge, among the specific metals and minerals and their deposits. The current knowledge of the extent of CRM resource potential and the locations of known CRM deposits in the Nordic countries are summarised in Figure B. The geological potential is fundamentally linked to the fact that the Nordic countries have a bedrock similar to the major mineral-rich countries globally, and together represent a large (ice-free) land area comparable in size to the most mineral-rich parts of either Canada, USA, Australia, South Africa, or Brazil.

For an overwhelming majority of the EU2020 CRMs, we find that there is moderate to major resource potential within the Nordic countries. Table A shows how some of the Nordic CRM resources stand out in a European and, in part, even a global comparison. In this context, it is important to note two general rules of economic geology: 1) a large number of known small deposits and occurrences indicate a larger potential for a mineral commodity, and 2) that all that is present in the known resources represents merely a fraction of all that can be found and extracted through additional exploration.

Table A. The most important CRMs from a Nordic perspective. These are the ones with the largest known resources and resource potential for a commodity or have other major significance within Europe.

Commodity	Main application in green technologies; share of global resources if major; relevance for current European mine production (excluding Russia and Ukraine)
Cobalt	Essential for many electrode types in Li-ion batteries; *100 % of European mine production*
Graphite	Essential for electrodes in Li-ion batteries; *nearly 90 % of European mine production*
Hafnium	Solar cells, infra-red and fibre optics; *no European mine production; 100 % of European resources*
Lithium	Li-ion batteries; *no European mine production for batteries; battery-grade production under development in Finland*
Niobium	Superalloys in power generators, turbines, super-conducting magnets; 8 % of globally known resources; *no European mine production; 99 % of European resources*
Platinum group metals	Essential in fuel cell and hydrogen power technology; extensive electronics applications; *100 % of European mine production; 99 % of European resources*
Rare earth elements	Magnets for electric motors and generators in vehicles and wind turbines; fuel cells and batteries; 9 % of globally known resources; *no European mine production*
Silicon metal	Solar panels, semiconductors, silicon anodes in future Li-ion batteries
Tantalum	Capacitors and other electronics; *no European mine production; 99 % of European resources*
Titanium	Light-weight alloys for vehicles and electricity-related structures of all kinds; 25 % of globally known resources; *100 % of European mine production; 90 % of European resources*
Vanadium	Stationary redox batteries (large-scale energy storage); *10 % of the globally know resources*

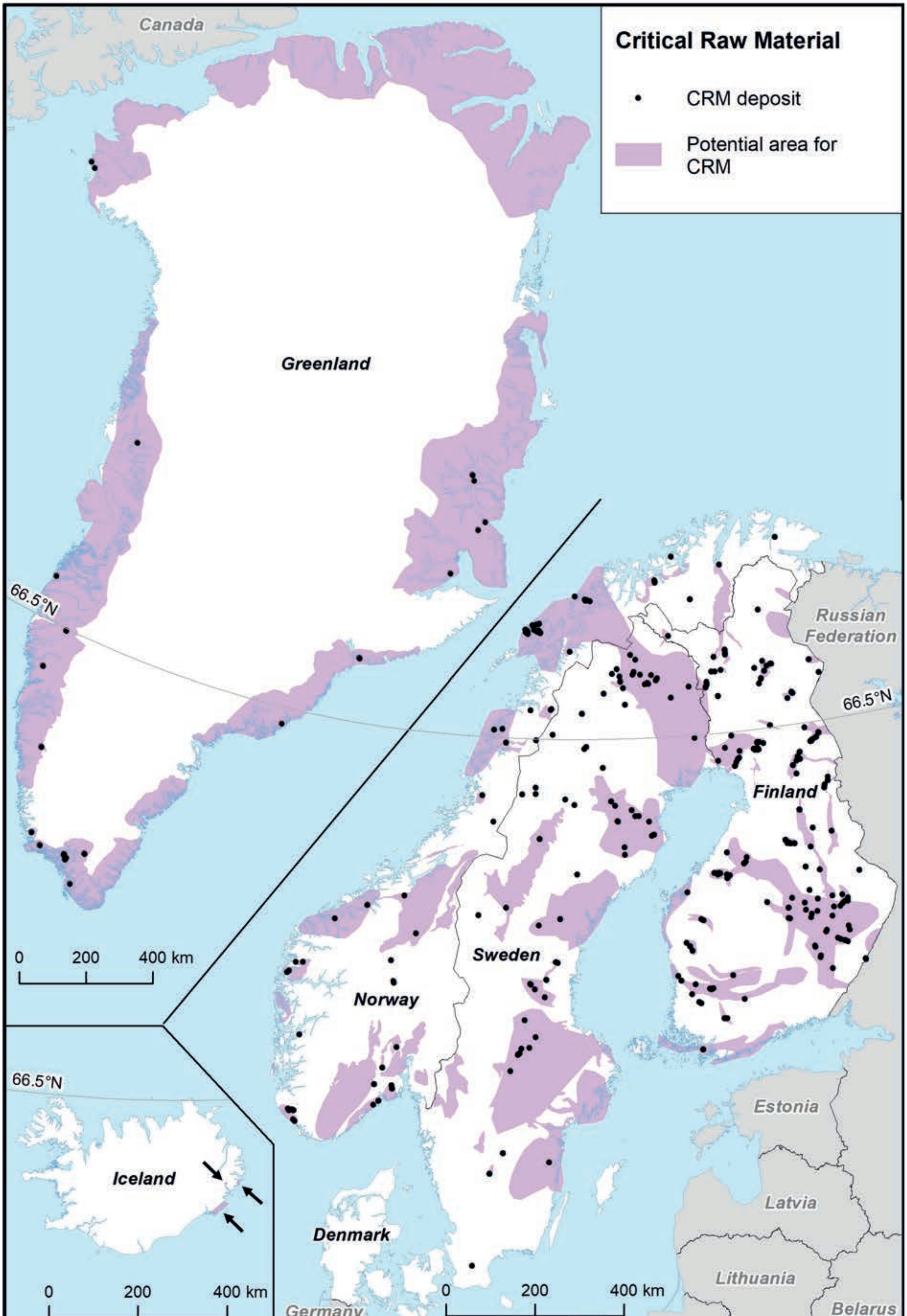

Figure B. Locations of deposits with known critical raw material resources and areas with known or assumed potential for additional CRM resources in the Nordic countries.

Recycling will increase and cover part of the future raw material demands of the society, but singularly aiming towards a low-carbon emission society means that mining will remain as the main source of the necessary raw materials. A significant part of metal recycling already takes place by means of the mining, refining, smelting and manufacturing industries. Additionally, other metals and minerals may become critical for the Nordic countries and Europe. Competition for all raw materials will, consequently, increase between the industry sectors. Hence, much larger volumes of primary mineral-based raw materials are needed than what can possibly be accessed through recycling.

In this report, we show that there is much of relevant information for the Nordic countries, but also major gaps in fundamental data and information. Hence, we recommend the following work to be done as immediate actions. Cooperation beyond the organisations who produced this report is recommended for some of the topics. As we list many major research topics, this most probably means work in 3 to 5 full-scale projects (lasting 3-4 years, but could have follow-ups beyond that) which should mutually cooperate to achieve common general goals:

1. **Research on how to initiate or expand CRM exploration, sustainable domestic production and processing capacity from *primary sources*.** This is the core of all work to be done and includes both metals that are currently extracted and those that are sparsely or not at all recovered from the presently mined ores. The work also includes improvement of recovery rates of the metals extracted from the ores.
    - In order to contribute to meet raw materials needs, the Nordic mineral resource potential should be thoroughly investigated. With a few exceptions (such as Co, PGMs, Ti and V), the knowledge base is poor for most of the critical raw materials.
    - Assess poorly known but high-potential mineral deposit types in geologically favourable areas and identify which data can be generated by government institutions to provide the foundation for or accelerate private industry investments.
    - Produce maps indicating potential areas and compile relevant geoscience and industry data in easily accessible data packages, that in turn are readily updated as new data and other information become available.
    - The Nordic sea floor resource potential should be assessed in the CRM context. There is potential for, e.g., manganese deposits enriched in cobalt.
    - Investigate energy-efficient mineral processing (beneficiation, smelting and refining) and CRM-based component production technology: the existence of facilities for this within an economic area (the Nordic countries or any economic alliance) is an essential part of the secure supply of materials needed for the transition towards low-carbon energy production and utilisation, besides other industrial demands.

2. **Research on CRM amounts and distribution, and how to expand or initiate sustainable domestic production and processing capacity from *secondary sources,*** including mine, refinery and smelter side streams and waste, and recycling of end-of-life products (a circular economy approach).
   - Accelerate and initiate inventory of CRMs and other raw materials in mine, smelter and refinery waste areas, and other anthropogenic deposits, both old and those currently increasing in volume. Some of the raw material demand for a low-carbon society could be covered from such industry side streams which still today remain unexploited.
   - The results, if commercialised, would also mean decreasing discharges of toxic materials into the ambient environment.

3. **Create a *Nordic database* on primary and secondary resources.** This database would be created by using both existing and new data on known deposits. The database needs to contain much more than just the basic, existing, deposit data: all new data including indications of CRM and other green energy transition raw material should be incorporated. The database should also include anthropogenic (secondary) resources and information on mineral potential regions. It hence is closely linked to recommendations 1 and 2.

4. **Investigate and characterize *the entire metal and mineral demand***, and the potential supply situation for the green energy technologies, as many of these commodities are presently not classified as critical. This work should include:
   - Forecasts on the future material flow in short, medium and long term.
   - Investigation on entirely new types of mineral-based commodities, such as the basalt-based fibres and other mineral products derived from primary and secondary sources. The successful advance in basalt fibre production and other NordMin-funded cooperation should be continued.

This work was led by Geological Survey of Finland (GTK); the other participants are the Geological Survey of Sweden (SGU), the Geological Survey of Denmark and Greenland (GEUS), the Ministry of Mineral Resources of the Government of Greenland, the Geological Survey of Norway (NGU), the Norwegian Directorate of Mining, Reykjavik University (RU), and the National Energy Authority of Iceland (NEA).

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1 Introduction

The so-called **Green Energy Transition** represents fundamental changes in how we produce, use and store energy. Such major technological changes that affect the entire society and industry also lead to the emergence of new and rapidly increasing demands for specific raw materials (Bobba et al. 2020, Hund et al. 2020). These are the metals and minerals which are vital to the production of new technologies for energy production, storage, transmission, and efficiency (Figures 1 and 2). Nations are dependent on a range of critical minerals and materials that are the building blocks of the products we use every day. A majority of these required metals and minerals are also classified as Critical Raw Materials (CRMs) for the EU. At the core of this classification is that the CRMs are defined as ***raw materials of high importance to the economy and whose supply is associated with a high risk of disruption*** (Blengini et al. 2020). This concept of criticality is further described in Section 2.1 and onwards.

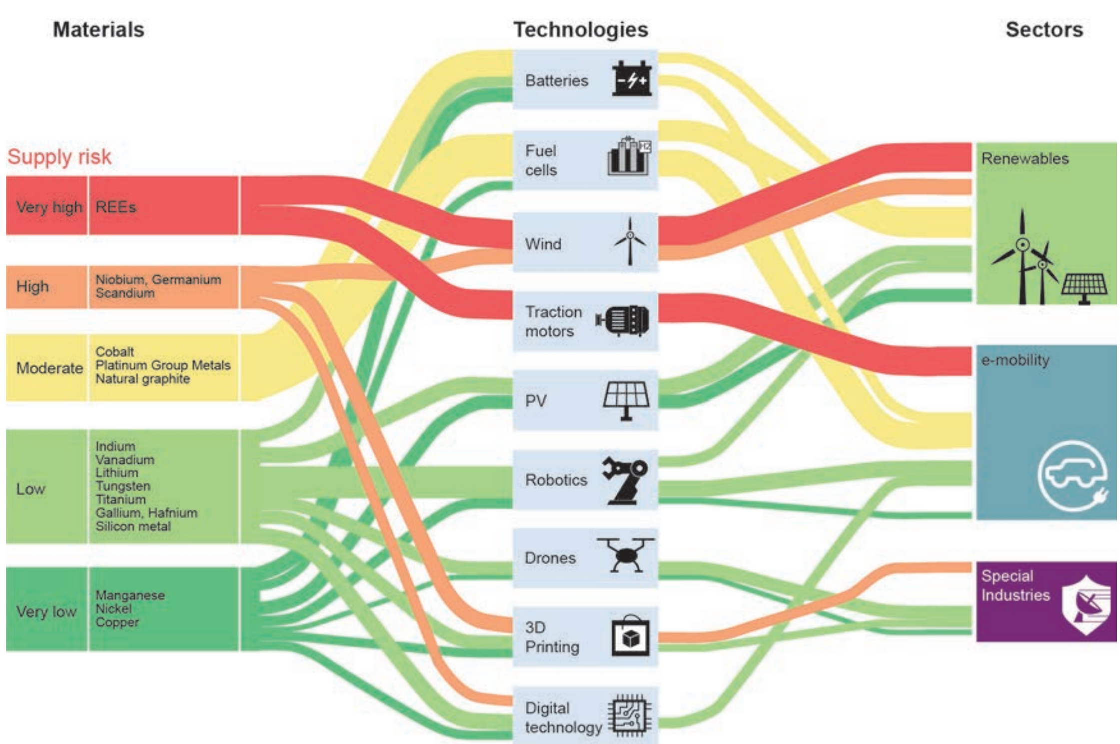

Figure 1. Supply risk of raw materials needed in green energy transition and special industries (modified from Bobba et al. 2020).

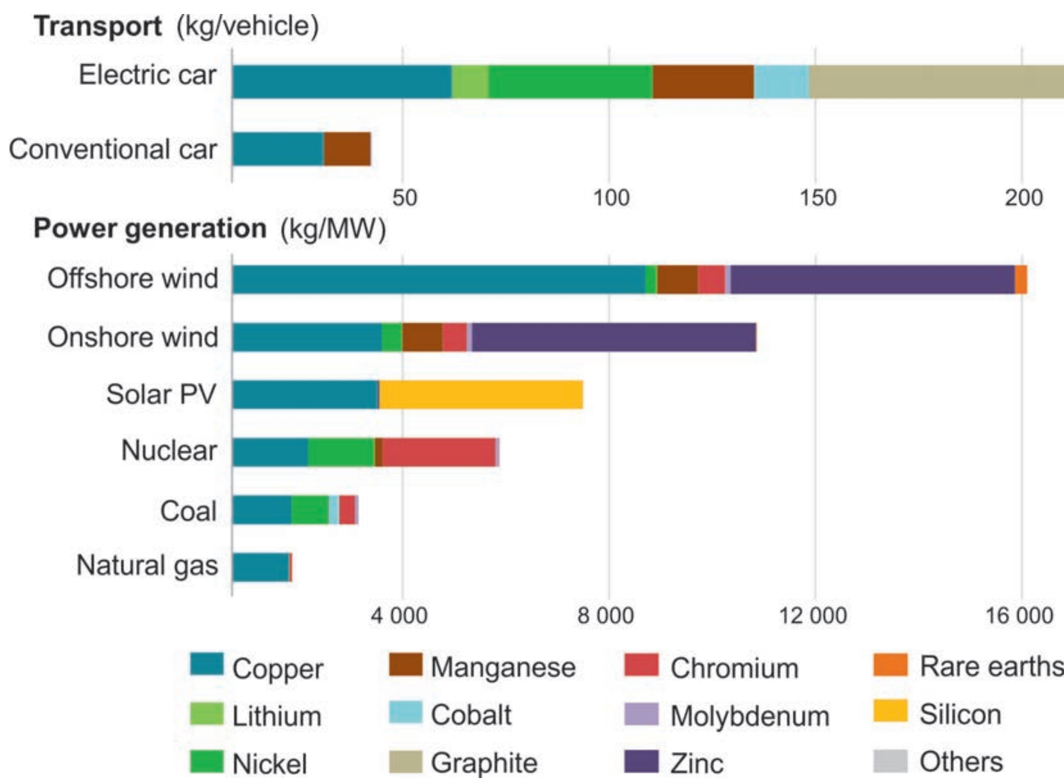

Figure 2. Examples on how much more specific metals the green energy transition will demand compared to fossil-fuel based counterparts (modified from IEA 2021). In order to focus on the more expensive and/or rare metals and minerals, iron and aluminium are not included in the figure, albeit having larger share by weight than the other metals (especially iron). Of the commodities depicted, only copper and zinc have a very low supply risk; manganese (Mn), chromium (Cr), molybdenum (Mo), and nickel (Ni) are not included in the present EU CRM list, but have supply risks currently just below the critical threshold for the EU (Eynard et al. 2020). PV = photovoltaic applications, i.e., solar cells and associated technologies.

Secure and resilient supply chains of the CRMs are essential for the economic security of any country, including the Nordic region and Europe, to facilitate a technological leadership. Many of the CRMs are furthermore essential in climate change control, to achieve a low carbon society. In the context of the green energy transition, it is important to stress that recycling is far from enough to meet the increasing projected demand for CRMs (e.g., Hund et al. 2020, IEA 2021, Schütte 2021). For example, global demand for lithium and graphite, two of the most important raw materials for electric vehicle batteries, is estimated to grow by more than 40 times up to 2040 in a scenario where the world achieves its present climate goals. Even with forecasted increases in recycling, an IEA report (2021) suggests that "recycled quantities of copper, lithium, nickel and cobalt from spent batteries could reduce combined primary supply requirements for these minerals by around 10 %". Hence, there is an urgent need for mapping the availability of, and potential for CRM supply also from the Nordic bedrock. In conjunction with this, an in-depth assessment of the present and near-future demand situation from within the Nordic industrial ecosystems should also be done.

This report focuses on the potential for all the Nordic countries; Denmark, Finland, Iceland, Norway, Sweden, and Greenland, to supply such critical raw materials, and covers the land area of them. We do recognise the potential, although modest compared to total demands as noted above, of recycling to providing raw materials for the energy and other sectors of industries – however, the time constraints for producing this report did not allow us to address this. Given that the mineral resources and exploitation in Denmark are limited to limestone, chalk, salt, clay and aggregates (sand, gravel and crushed rock) resources, the country is not discussed further in this report. The total land area of the Nordic countries, excluding Denmark and the ice-covered part of Greenland, is 1.63 million km^2 (Finland 338,000, ice-free part of Greenland 415,000, Iceland 103,000, Norway 324,000, and Sweden 450,000 km^2). One may compare that with the size of the EU, 4.33 million km^2. This helps to understand that the Nordic countries are not a small part of Europe and, to some extent explains the extensive mineral potential of this region. However, the main explanation for the Nordic mineral potential is the long and complex geological evolution of its bedrock and cover units.

As to the specific CRMs, we only consider those defined as critical by the European Commission in 2020 (Blengini et al. 2020, Bobba et al. 2020). The reasons for this are as follows: the Nordic countries are part of Europe, three of them (Denmark, Finland, Sweden) are members of the EU, and the EU countries represent the largest trading partner for all the Nordic countries. An additional reason is that with the limited framework of the current report, it was not possible to investigate which geological raw materials would be most critical for particular Nordic industries and sectors. The concept of raw material criticality is described in Section 2.2. As the concepts of 'mineral resource' and 'mineral or ore reserve' are also significant in understanding the topics of this report, we describe the essentials of them in Section 2.3.

The main part of this report describes the mine production, known and assumed resources, and assessments of the general resource potential for CRMs in the Nordic countries (Table 1 and Sections 3 and 4). In addition, we also briefly cover some of the metals which are essential for the green energy transition, but which are presently not defined as critical for the EU. All this is summarised at the end of the report, complemented by a list of recommendations (Section 5) on in-depth research that is needed to bridge the identified knowledge gaps on the matters presented in this report.

Overall, we find the Nordic supply potential for CRMs in general to be relatively good, but with large variations, both regarding geological favourability within and between the countries, and in the state of knowledge among the specific metals and minerals. For example: while the resource potential for some of the most critical metals to e-mobility – cobalt, lithium and the rare earth elements – range from reasonably known and locally exploited resources in the Nordic countries, others, such as the typical "by-product metals" antimony, bismuth, gallium, germanium and indium, are only poorly known. This is outlined in more detail in Sections 3 and 4.

This project was led by Geological Survey of Finland (GTK); the other participants are the Geological Survey of Sweden (SGU), the Geological Survey of Denmark and Greenland (GEUS), the Ministry of Mineral Resources of the Government of Greenland, the Geological Survey of Norway (NGU), the Norwegian Directorate of Mining, Reykjavik University (RU), and the National Energy Authority of Iceland (NEA).

This work was fully funded by Nordic Innovation, an organization under the Nordic Council of Ministers. Nordic Innovation aims to make the Nordics a pioneering region for sustainable growth and works to promote entrepreneurship, innovation and competitiveness in Nordic business.

All abbreviations and the symbols of chemical elements used in this report are explained in Appendix 1.

Kevitsa nickel mine, Finland. Photo J.Brusila.

Table 1. CRMs with current (2020) mine, refinery and smelter production, resources and/or resource potential in the Nordic countries. Figures in tonnes of metal or mineral. At the bottom, there are three currently non-critical metals (copper, manganese, nickel) that also are essential in the green energy transition. PGM = Platinum Group Metals. For details, including the country-specific data, see the fact sheets in Section 3 and the CRM tables in Appendix 2.

Commodity	Mine production	Refinery and smelter production	Known resources[2]	Assumed additional resource potential[3]				
				Finland	Greenland	Iceland	Norway	Sweden
Antimony	0	0	28,3880	yes	yes	no	yes	yes
Baryte	0	-[1]	592,500	yes	yes	yes	yes	yes
Beryllium	0	0	990	yes	yes	no	yes	yes
Bismuth	0	0	677	yes	yes	no	yes	yes
Cobalt	1,559	19,502	489,700	yes	yes	no	yes	yes
Fluorspar	0	-[1]	4,240,000	no	yes	yes	yes	yes
Gallium	0	0	21,300	yes	yes	no	yes	yes
Germanium	0	0	0	yes	yes	no	yes	yes
Graphite[4]	10,000	10,000	30,654,000	yes	yes	no	yes	yes
Hafnium	0	0	1,100,000	yes	yes	no	no	yes
Indium	0	0	0	yes	yes	no	yes	yes
Lithium	0	0	78,240	yes	yes	no	no	yes
Niobium	0	0	6,612,000	yes	yes	no	yes	yes
Platinum group metals	2.134	not reported	1,150	yes	yes	no	yes	yes
Phosphorus	182,620	-[1]	260,000,000	yes	yes	no	yes	yes
Rare Earth Elements	0	0	35,700,000	yes	yes	no	yes	yes
Scandium	0	0	50,000	yes	yes	no	yes	yes
Silicon metal[4]	170,000	276,000	31,600,000	yes	yes	no	yes	yes
Tantalum	0	0	1,093,692	yes	yes	no	no	yes
Titanium[4]	189,000	21,582	180,200,000	yes	yes	yes	yes	yes
Tungsten	0	0	7,500	yes	yes	no	yes	yes
Vanadium	0	0	6,938,400	yes	yes	no	yes	yes
Copper	135,610	396,400	18,540,000	yes	yes	yes	yes	yes
Manganese	0	490,000	10,688,000	yes	no	no	yes	yes
Nickel	41,429	183,005	7,640,000	yes	yes	no	yes	yes

1 For these commodities, 'smelter or refinery production' is not relevant.
2 Includes both mineral resources according to the current industry standards (as required by stock exchanges) and resources not according to such standards; the latter are often called 'historic' resources. The figures given are rounded to the lowest precision of the respective data available, hence the sums in this column are not exactly the same as what one gets from the fact sheets and the CRM tables.
3 Potential for additional discoveries. 'no' indicates no known indications of a commodity resource, but does not outright mean there is no potential – comprehensive information typically is lacking. Resource potential of the sea floor is not included.
4 For graphite, silicon metal, titanium, the presented figures may somewhat deviate from the real production figures and represent multi-year averages.

2 Raw material criticality and the green energy transition

2.1 Critical metals and minerals for the green energy transition

As defined by the EC critical raw materials (CRM) are those raw materials that have a high importance to the economy of the EU and whose supply is associated with a high risk of disruption, as specified by the two parameters Economic Importance (EI) and Supply Risk (SR). In September 2020 the EC published the fourth list of CRMs (see Table 2 in Section 2.2), based on an assessment of 83 individual materials dominated by metals and minerals. A significant number of the classified CRMs are also critical for the technologies forming the core of the recently initiated green energy transition of our societies.

The metals and minerals essential to the green energy transition share many of the same complex sourcing challenges relating both to risks of supply cut-downs and environmental and ethical issues in the presently producing countries. Among the most important of them are those directly related to energy production, energy efficiency, and energy storage (Figures 1–3). All three of these major fields of de-carbonisation technology rely ultimately on our access to steel and base metals (Al, Cu, Ni, Zn) and specific critical metals and minerals, exemplified by 1) rare earth elements (REEs) for e-vehicle traction motors as well as wind power generators, 2) cobalt, lithium, vanadium, and graphite for e-vehicle and other battery technologies, and 3) boron, indium, gallium, germanium and silicon for solar energy production applications (Carrara et al. 2020, Hund et al. 2020, Latunussa et al. 2020, Nassar & Fortier 2021). Besides several other crucial alloying metals, niobium is needed in a multitude of roles for adding strength while decreasing weight of special steel constructions such as wind generator structures, e-vehicles etc.

It is worth noting also that the dramatically increasing demand for these metals and minerals, through the large-scale and rapid implementation of green energy-technologies, will be in full competition with all other, still existing fields of application with large associated demands for the same raw materials (Figure 3). IEA (2021) reports that the energy sector demand for, e.g., cobalt will increase by 6 to 30 times and that of the REEs by 3 to 7 times compared to the demand of today. Taking all the industrial sectors together, the production of both current mines and mines under construction, plus the forecasted recycling, will not be able to cover the metal and mineral demand even for the lower range of the forecasts (e.g., Hund et al. 2020, IEA 2021).

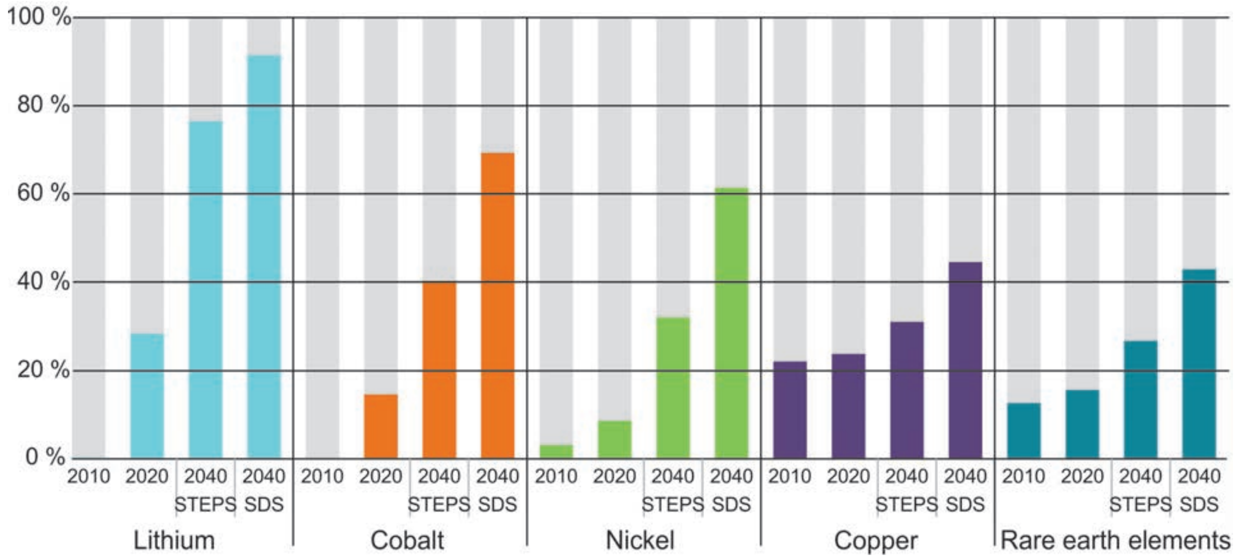

Figure 3. Predicted increases in demand for a selection of important metals for green energy applications. The figure shows how the demand from the decarbonisation technologies will overtake (and add to) the demand from other major manufacturing sectors. Neodymium demand is used as an indicator for the rare earth elements (REEs). STEPS = 'Stated Policies Scenario', an indication of where the energy systems are heading based on today's policies and policy announcements; SDS = 'Sustainable Development Scenario', indicating what would be required when aiming to achieve the Paris Agreement goals. Modified from IEA (2021). It is important to note that 1) the demand of the information and communication technology (ICT) is part of the 'other sectors' (of the metals depicted, the ICT sector demand is the most significant for the REEs but not negligible for Co, Cu and Ni), and 2) that the total demand of a commodity is not assumed to be constant, but in all forecasts assumed to multiply.

2.2 The concept of criticality of a raw material

As previously stated, critical raw materials (CRM) are defined as *raw materials (RM) that both have a high economic importance (EI) and a large supply risk (SR)* in the economy of a country or some other region under consideration (Blengini et al. 2020). To be classified as critical, a commodity must, therefore, be both in production somewhere in the World and consumed in the specific market that the criticality is assessed for. A CRM does not need to be expensive nor rare, even though several are.

The European Commission (EC) has evaluated EU's CRMs in 2011, 2014, 2017, and 2020 (Blengini et al. 2020) in comprehensive and summarising reports of more than 2000 pages in several volumes. USA also has evaluated their CRMs in similar comprehensive studies and is consistently evaluating the issue (Schulz et al. 2017, Nassar & Fortier 2021, The White House 2021). Similar assessments have also been done by many other countries, such as Canada and Australia, most probably also by China and Russia, but very detailed reports have, to our knowledge, not been published.

In this subsection, we explain the concept methods for defining the CRMs and how they are ranked, following the methods used by the EC (European Commission 2017).

Economic importance (EI)

The parameter EI aims at providing comparability and insight on the importance of a material for the EU economy in terms of end-use applications and the value added (VA) of corresponding EU manufacturing sectors in the *Nomenclature of Economic Activity Codes* (NACE) at the 2-digit level. The economic importance is corrected by a substitution index related to technical and cost performance of potential substitutes for the material in individual applications (e.g., Blengini et al. 2020).

If a raw material is used in a group of industrial sectors, the EI is calculated by multiplying the share of end use in one sector and the VA for that sector which again is multiplied by an index for substitution. This is repeated for each sector and the EI for the particular CRM at hand is produced when all sectors are summed up.

Supply risk (SR)

The parameter SR reflects the risk of a disruption in the supply of a specific raw material. It is based on the concentration of primary supply of raw materials from producing countries, considering their state of governance and trade aspects. The concentration of primary supply is determined by calculating the *Herfindahl-Hirschman Index*, HHI (Rhoades 1993), while the country's governance is determined according to the World Governance Index (WGI) as defined by the World Bank (Kaufmann et al. 2010).

To simplify: if we, for example, have three countries sharing the world production of a RM, the supply risk is calculated by multiplying the HHI, WGI, and the fraction of world production of each country, and adding these numbers for all three countries. In practice, the calculation used by the EC is much more complex since the SR is modified by the following factors:

a) Domestic production relative to import and re-export
b) Special trade agreements between selected countries which secure supply
c) Substitution (that could take place if a supply shortage occurs)
d) Degree of recycling

Each of these factors is furthermore defined by several parameters.

The EC has taken all these modifying factors into account for their SR calculation (Blengini et al. 2017, 2020). When this is done, one ends up with a list of RMs, each with a value for EI and SR, and certain thresholds defining what is critical or not critical. In 2020, the EC used a threshold of 1 for SR and 2.7 for EI (Figure 4). The list of the EU2020 CRMs is given in Table 2.

Table 2. The EU 2020 list of critical mineral raw materials (Blengini et al. 2020), including chemical symbols or formulae. Commodities with resources in the Nordic countries are in bold. HREE = heavy rare earth elements, LREE = light rare earth elements, PGMs = platinum group metals. Also note that all phosphorus is derived from phosphate minerals.

Antimony (Sb)	**Fluorspar** (CaF_2)	Magnesium (Mg)	Strontium (Sr)
Baryte ($BaSO_4$)	**Gallium** (Ga)	**Natural Graphite** (C)	**Tantalum** (Ta)
Bauxite	**Germanium** (Ge)	**Niobium** (Nb)	**Titanium** (Ti)
Beryllium (Be)	**Hafnium** (Hf)	**PGMs**	**Vanadium** (V)
Bismuth (Bi)	**HREEs**	**Phosphate rock** (PO_4)	**Tungsten** (W)
Borates (BO_3)	**Indium** (In)	**Phosphorus** (P)	
Cobalt (Co)	**Lithium** (Li)	**Scandium** (Sc)	
Coking Coal	**LREEs**	**Silicon Metal** (Si)	

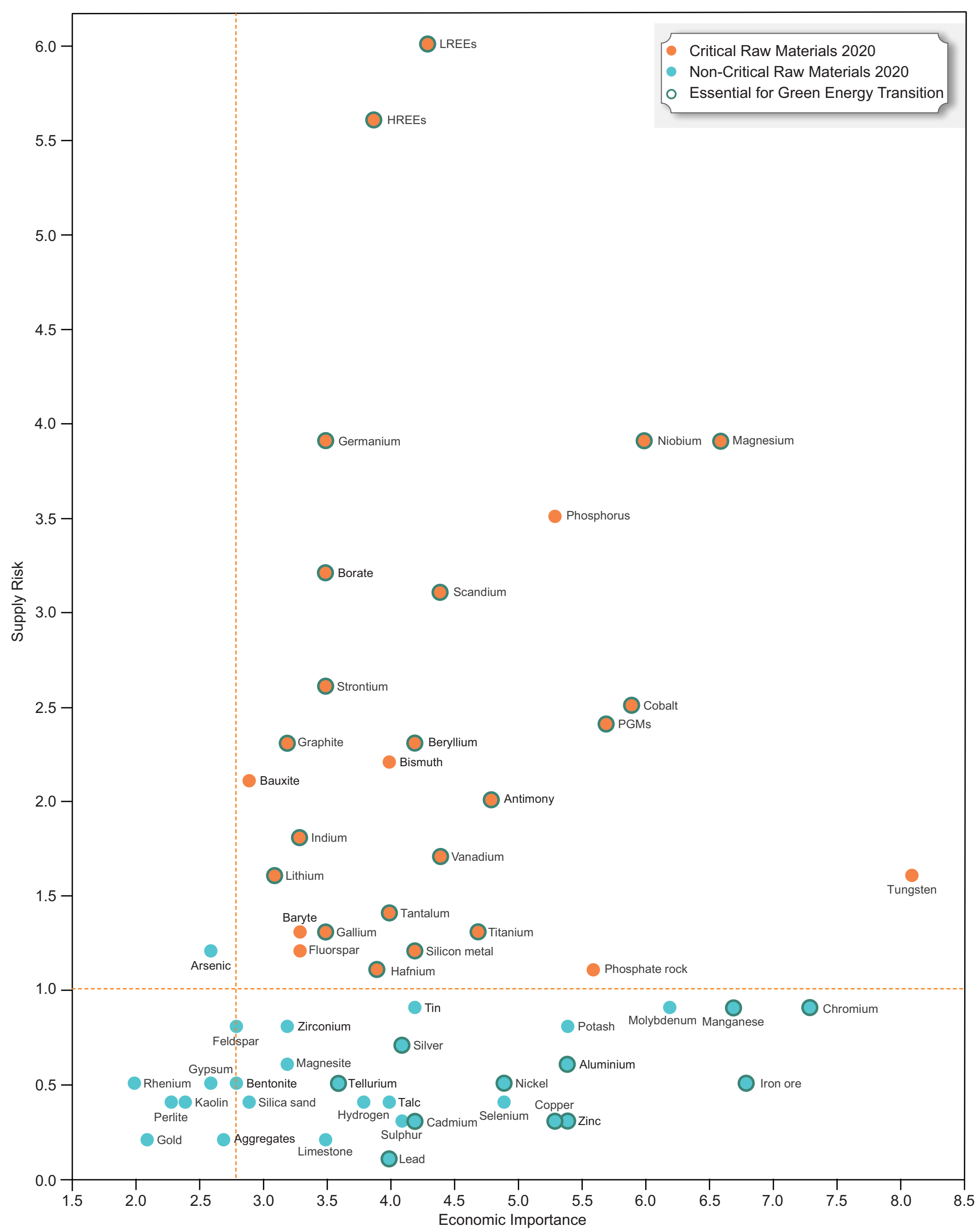

Figure 4. Plot of critical and non-critical raw materials in the EU 2020 evaluation (modified from Blengini et al. 2020). We have marked all the commodities that are needed in the green energy transition, whether currently defined as critical or not. For abbreviations, see caption of Table 2.

The life cycle of metals

For all raw materials, their life cycle is long and complex. In Figure 5, Latunussa et al. (2020) have used the life cycle of cobalt as an example. In this case, the relevant steps comprise exploration, extraction, processing, manufacturing, use and recycling. ***If one of these steps takes place in a setting defined as critical, the whole chain will be critical***. This is a very important aspect. For example, China dominates the world production of rare earth elements (the REEs). If mining starts on an REE deposit in the Nordic countries but concentrates from that production must be sent to China for refining and metal oxide production, the criticality will not be changed, all other things being equal.

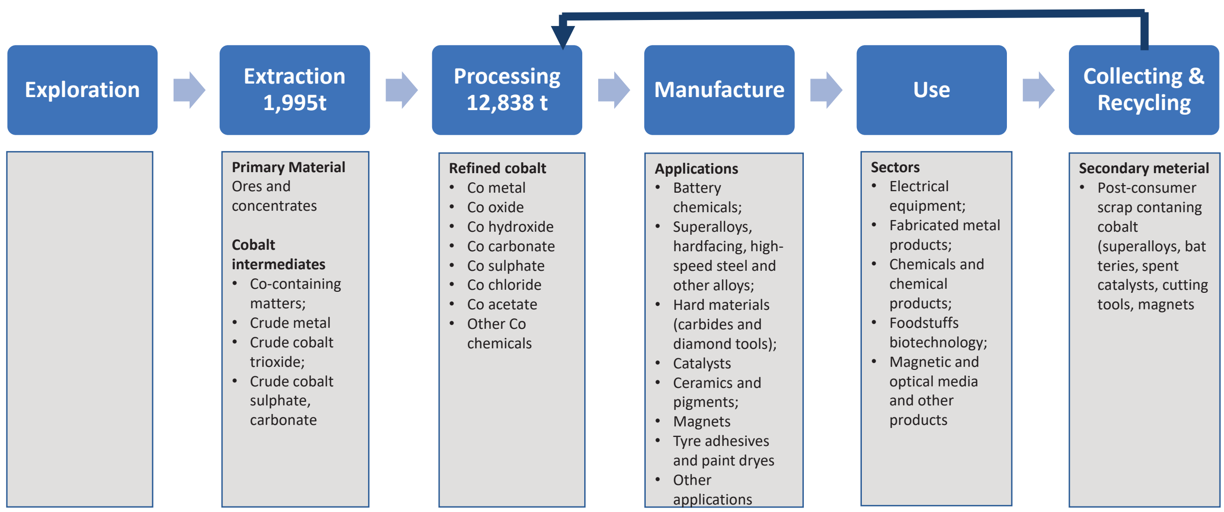

Figure 5. The life cycle of cobalt (Latunussa et al. 2020). Tonnages shown (Extraction = mining, and Processing = refining) are those for the Nordic countries in 2020. After extraction, the subsequent steps commonly take place in different countries, thus yielding a different criticality level for each individual step of the life cycle of a typical geological raw material.

Metal companionality

Most metals and, in particular, the CRMs are so-called ***by-product*** metals or '***companion metals***', all depending upon how their deposits formed and which are their preferred host mineral(s). Each CRM typically occurs in 'The wheel of metal companionality' (Figure 6) together with one or two more common metals and can only be produced as part of production of such main metal(s) (Nassar et al. 2015). Here we see for example that cobalt (Co) and nickel (Ni) are companions and to increase the production of cobalt it is necessary to increase the production of nickel. This can have direct consequences for the economy of metal production. For example, increased nickel production to get the needed cobalt can result in overproduction and a reduced global nickel price level, thus making the steps of mining and extraction less profitable in total and, further, reducing the economic interest in mine production of cobalt.

Another significant example of the effects of companionality and by-product issues is given by vanadium. Vanadium redox stationary batteries are seen as one of ready-to-use solutions for storing energy from solar and wind powered plants. Bushveld Metals (2020) report: "Over 70 % of vanadium currently comes from co-production, which is driven by steel and iron ore fundamentals. This co-production is primarily driven by steel and iron ore market dynamics rather than vanadium fundamentals, and co-producers are currently operating close to full capacity." It is forecasted that the demand for vanadium in large-scale stationary energy storage systems linked to wind and solar power, will eventually overtake all other uses of vanadium (e.g., Hund et al. 2020). As there are no indications that demand of vanadium is decreasing in other major sectors of the relevant industries, developing new vanadium deposits into the extraction stage will become essential.

On the other hand, the companionality wheel shows where there can be additional, but currently poorly known CRM resources. Here is another indication of possible additional resources also for the Nordic countries where we have a large number of old, closed and abandoned mines and unexploited ore showings, with little or no information other than that they, for example, were mined for nickel at one point in time. Such sites represent rock volumes where geological processes have resulted in enrichment of nickel and by all probability also the companion elements like cobalt, that could be targets for new investigations and mineral exploration. As the companionality arises from chemical similarity between elements, it also affects the metals potentially available in resources in secondary accumulations, such as mine, refinery and urban wastes.

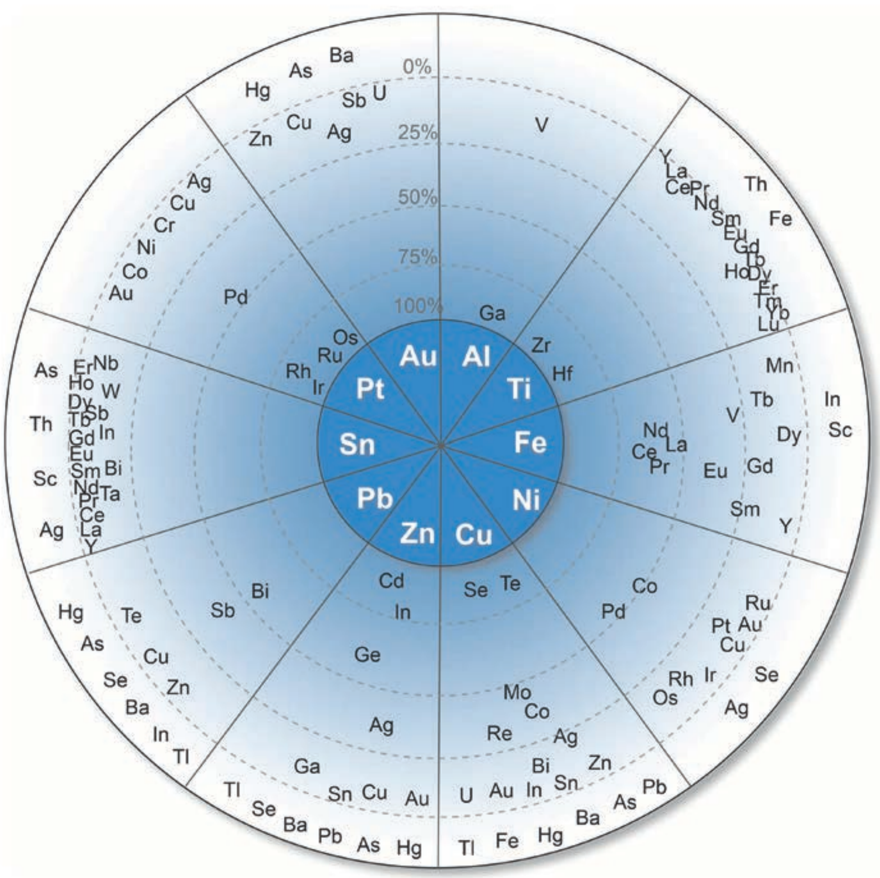

Figure 6. The wheel of metal companionality. Main metals are in the inner circle and, with decreasing strenght of relationship in their geological occurrences, their companion metals are distributed outwards (Nassar et al. 2015).

2.3 Definition of mineral resource and mineral or ore reserve

Mineral resource classification is the classification of mineral resources based on an increasing level of geological knowledge and confidence (Figure 7). A ***resource*** is that amount of a geologic commodity that exists in both identified and undiscovered deposits, and ***reserves*** are that subgroup of a resource, which have a known size, and can be exploited at a profit (e.g., CRIRSCO 2013).

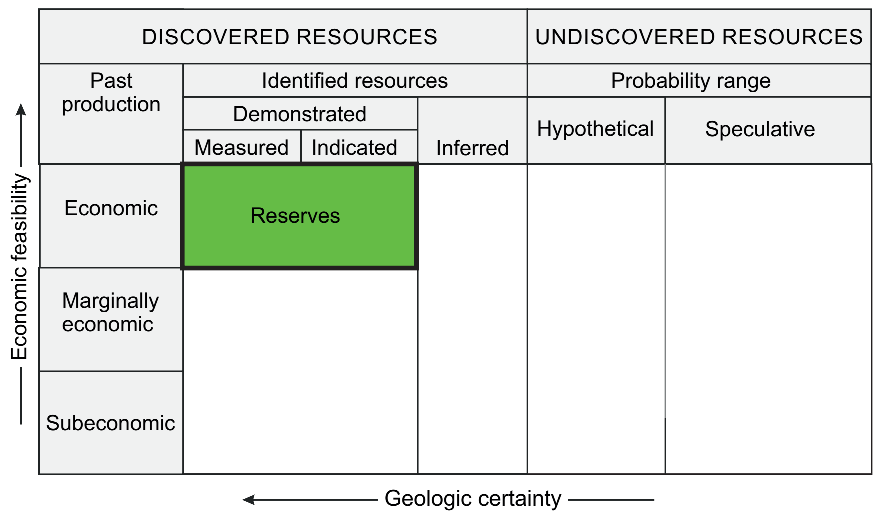

Figure 7. Classification of mineral resources and reserves, modified from USGS (2000). Economic feasibility increases upwards and geological certainty increases to the left. Only economic ore, i.e., reserves, are mined. Hypothetical are the undiscovered resources in known to occur types of mineral deposits in favourable geological settings where other well-explored deposits of the same types are known to occur. Speculative resources may occur either in known types of deposits in favourable geological settings where mineral discoveries have not been made, or in types of deposits as yet unrecognised for their economic potential.

The '*Mineral Reserve*' refers to the economically mineable part of a Measured or Indicated Mineral Resource demonstrated by at least a preliminary feasibility study. For both the Measured, Indicated and Inferred classes you know the quantity, grade or quality and densities, shape and physical characteristics of the ore body. However, the estimated level of confidence from the Measured, Indicated to Inferred groups decreases due to, e.g., less geological knowledge, limited information and/or less sampling. A 'Qualified Person' may classify the estimation of the Mineral Resource and Mineral Reserve of economic interest.

'Undiscovered' hypothetical resources may reasonably be expected to exist in known mining districts or incompletely explored terrains where geology allows known deposit type(s) to exist. Speculative resources are Undiscovered resources that may occur either in known types of deposits in favourable geological settings where mineral discoveries have not been made, or in types of deposits as yet unrecognised for their economic potential (USGS 2000).

Figure 7 schematically shows how the currently mineable ore (reserves) is just part of the known resources and a fraction of the total which is in ground, potentially available for extraction – even if not profitable to mine today. The reasons why not all that are in the currently known or reported reserves and resources are not just lack of knowledge but also because for a mining company it simply is not sensible to invest huge amounts in drilling everything. What a company needs to know as resources and reserves can be anything for the next 10 to 30 years of planned mine production (e.g., Meinert et al. 2016).

In this report, we consider all resources, except the speculative ones, when reviewing the Nordic CRM potential.

3 Production and resources of critical metals and minerals in the Nordic countries

In this section, we describe the mine and refinery production, and known and assumed resources of the CRMs, copper, manganese and nickel in the Nordic countries. The main tools of presentation are the commodity fact sheets, maps with the location of known deposits and mineral-potential domains. The fact sheets also include global production and resource data, and the current and forecasted future uses of the commodities. The Nordic information in the fact sheets is mainly derived from our national mineral deposit databases and from the FODD (2020). Further background information for the fact sheets is available as tables in Appendix 2.

Each CRM is covered in a subsection, whereas the non-critical (as per EU 2020 definition) copper, manganese, and nickel are jointly represented in one subsection. Where necessary, an introductory text precedes the subsection. Note that we have not included all non-CRMs needed for the green energy transition, but selected to include only Cu, Mn and Ni, as these are also important as battery metals.

In the fact sheets below, the energy-related uses of the commodities are ***highlighted*** in bold italic letters.

Outcrop at Sinarsuk Ti-V deposit in SW Greenland. Photo J.Keiding.

3.1 Antimony (Sb)

Commodity	Antimony (Sb)	Data source
Uses of the commodity	Main uses: Flame retardants, ***lead-acid batteries*** Minor uses: Lead alloys, plastics, glass industry, stabilizers in plastic material, catalyst for polyester production, pigment together with other metals, ammunition. Future uses: ***Semiconductor industry,*** cheaper alternative to Indium-Tin-Oxides for LCD screens. Continues to be important, possibly increase, in flame retardants. Use in ***car batteries*** may decrease if lead battery use decreases.	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production. Known resources: Finland 2,554 t, Greenland 3,780 t, Sweden 19,885 t. Resource potential: Finland: Minor potential in copper-zinc and certain gold deposits. Greenland: Several Sb occurrences in central East Greenland associated with tungsten. The closed Black Angel Mine has Sb, but the host mineral went into the tailings. Iceland: Unknown. Norway: Several gold and sulphide occurrences in the Caledonides are locally enriched in antimony, but without quantitative data as yet. Sweden: Skellefte district and surroundings has additional potential.	Harpøth et al. (1986), Sternbeck et al. (2002), Lauri et al. (2018), FODD (2020)
Global production (2020)	153,000 t Sb	USGS (2021)
Main producing countries (2020)	China 52 %, Russia 20 %, Tajikistan 18 %	USGS (2021)
Nordic refinery and smelter production	None	

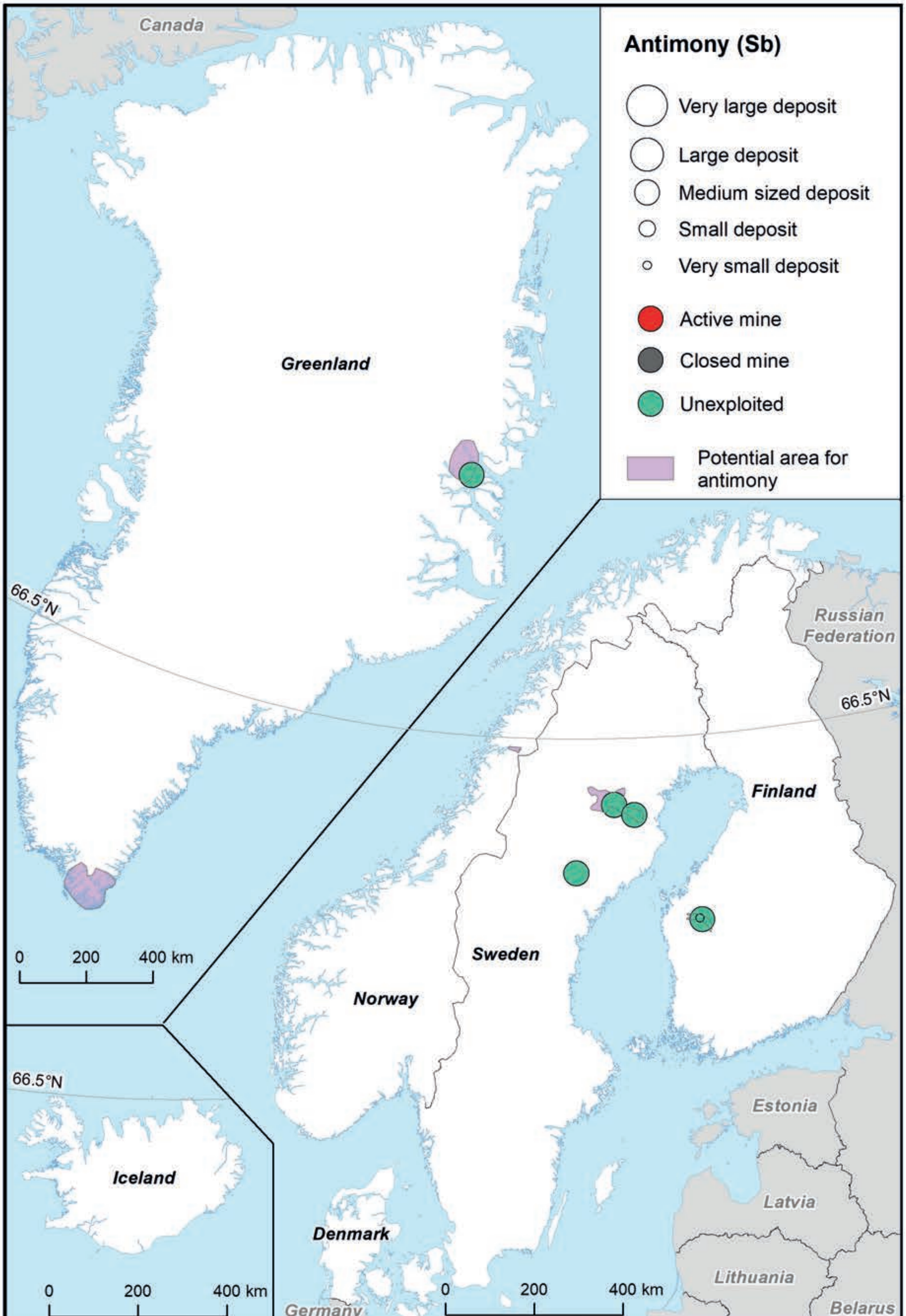

Figure 8. Locations of deposits with known antimony resources and areas with known or assumed potential for additional antimony resources in the Nordic countries.

3.2 Baryte (natural barium sulphate, $BaSO_4$)

Commodity	Baryte ($BaSO_4$)	Data source
Uses of the commodity	Main uses: Weighting agent in drilling muds (60 %), fillers (30 %) Minor uses: Chemicals (10 %), special concrete, special glass, bricks and tiles, electronics, ceramics and ***capacitors***. Future uses: Demand remains strongly linked to oil and gas exploration and exploitation, where expected to decrease in long term. Increasing demand in the construction, electronics, and the automotive industry.	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production in Nordic countries. Known resources: Greenland 592,500 t baryte. Resource potential: Finland: Baryte has earlier been produced from the Pyhäsalmi Cu-Zn mine. The surrounding area also has potential for baryte. Greenland: Resources identified at the 'Zebra Klint' and Bredehorn deposits, resources are probably in the order of several million tons. Iceland: Minor potential for baryte in Fáskrúðsfjörður, East Iceland. Norway: Baryte is common in Pb-Zn and Ag vein deposits (Bamble, Kongsberg) and the iron-rich parts of the Fen carbonatite. Sweden: Several deposits are known to contain baryte. The largest of these is the giant Aitik Cu-Au deposit. The others are small.	Harpøth et al. (1986), Franzson et al. (1992), Lauri et al. (2018)
Global production (2020)	7.5 Mt baryte	USGS (2021)
Main producing countries (2020)	China (33 %), India (27 %), Morocco (11 %), Kazakhstan 8.0 %	USGS (2021)
Nordic refinery and smelter production	Not relevant for baryte.	

Figure 9. Locations of deposits with known baryte resources and areas with known or assumed potential for additional baryte resources in the Nordic countries. The associated resource-potential area in Iceland is assumed to be very small, hence indicated by a black arrow.

3.3 Beryllium (Be)

Commodity	Beryllium (Be)	Data source
Uses of the commodity	Main uses: Copper-beryllium alloys (65 %). By industry sector: ***Electronic & telecommunications equipment*** (42 %), Transport and Defence (44 %) Minor uses: High-beryllium alloys (>40 % Be) in electro-optical systems in the space and aviation industries. Be metal applications consume on average 20 % of the production. By industry sector: ***Energy applications*** (8 %), Industrial components (6 %) Future uses: Defence applications, nonmedical and industrial X-ray products, ***semiconductor processing equipment*** and new types of beryllium alloys.	Sabey (2006), BRGM et al. (2017), USGS (2020, 2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production in the Nordic countries. Known resources: Finland 294 t, Greenland 65 t, Norway 630 t. Resource potential: Finland: Lithium deposits have Be as a potential byproduct. Greenland: Minor additional indications of Be resources. Norway: The Høgtuva area, where several small deposits occur within 8 km^2. Sweden: Minor historic production from Kolsva, Perstorp and other localities. The Yxsjöberg W-deposit contains elevated Be concentrations.	Lundegårdh (1971), Wilberg & Lindahl (1991), Stensgaard et al. (2016), FODD (2020)
Global production (2020)	240 t Be. The production is dominated by the US company Materion Corp.	Latunussa et al. (2020), USGS (2021)
Main producing countries (2020)	Mine production: USA 62 %, China 29 %, Mozambique 6 %	USGS (2021)
Nordic refinery and smelter production	None	

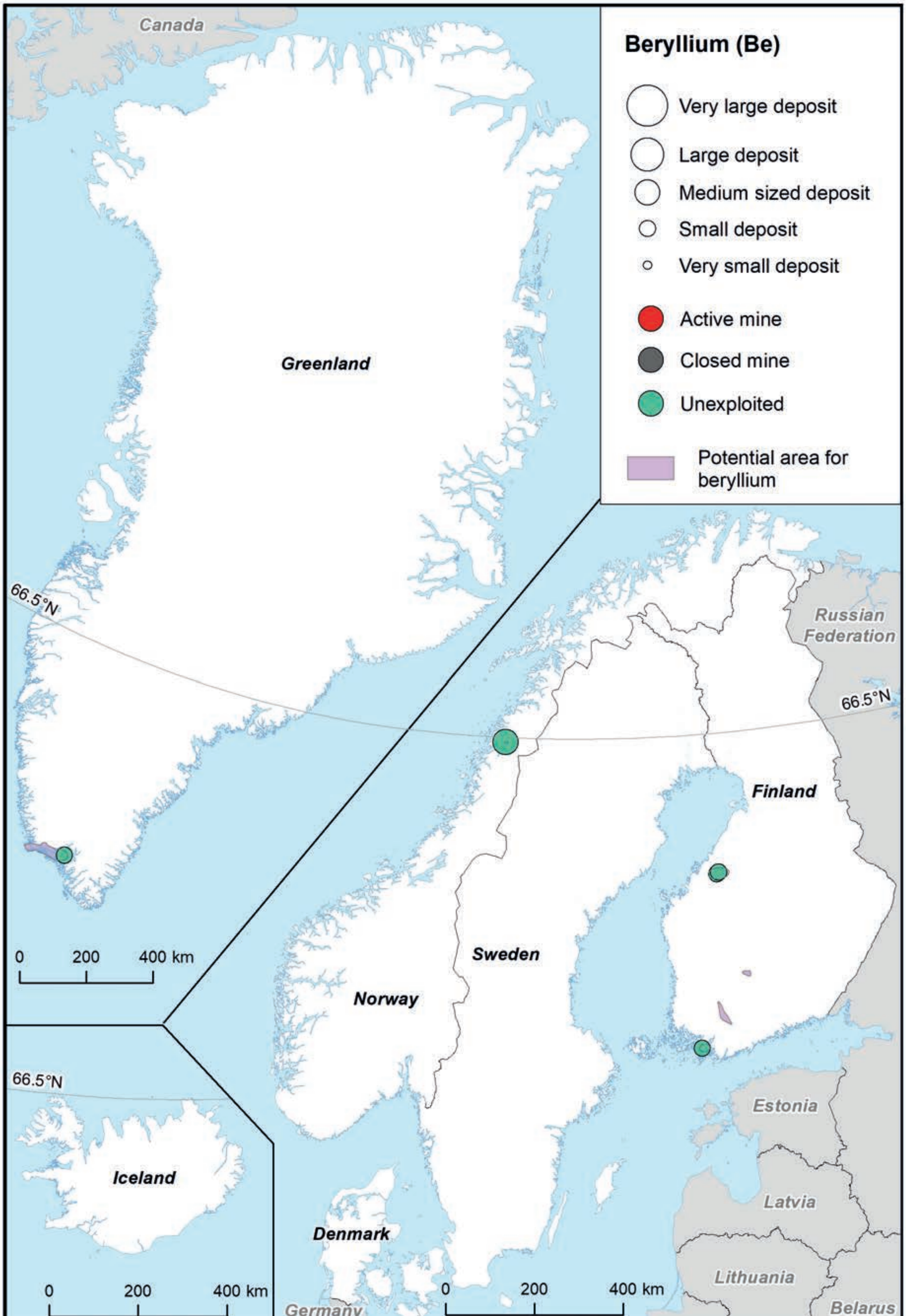

Figure 10. Locations of deposits with known beryllium resources and areas with known or assumed potential for additional beryllium resources in the Nordic countries.

3.4 Bismuth (Bi)

Commodity	Bismuth (Bi)	Data source
Uses of the commodity	Main uses: Chemicals, mainly pharmaceutical and cosmetics products (62 %), low-melting alloys (28 %), metallurgical additives (10 %) Minor uses: Coatings, pigments, and ***semiconductors*** Future uses: Demand in pharmaceuticals and solders increases. ***Semiconductors, thermoelectric materials and topological insulators***.	BRGM et al. (2017), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production. Known resources: Sweden 676 t Bi (Kankberg nya mine). Resource potential: Any copper, zinc and gold deposits may contain potentially recoverable bismuth. Finland: Bi concentration is reported from one copper-gold deposit in eastern Finland. Greenland: No assessment is made for Bi. Iceland: Unknown. Norway: Several sediment-hosted Zn-Cu deposits with up to 100 g/t Bi (e.g., in Røros). Sweden: Bi is known from many deposit types, of which a few have historic production.	Lauri et al. (2018), FODD (2020), SGU (2021)
Global production (2020)	17,000 t Bi (this is smelter production; mine production is not known)	USGS (2021)
Main producing countries (2020)	Refined Bi: China 82 %, Laos 6 %, Republic of Korea 5 %, Japan 3 %. Regarding mine production, China has the only mine in the World with Bi as a main product. Most Bi is byproduct from tungsten and lead ores.	USGS (2021)
Nordic refinery and smelter production	None	

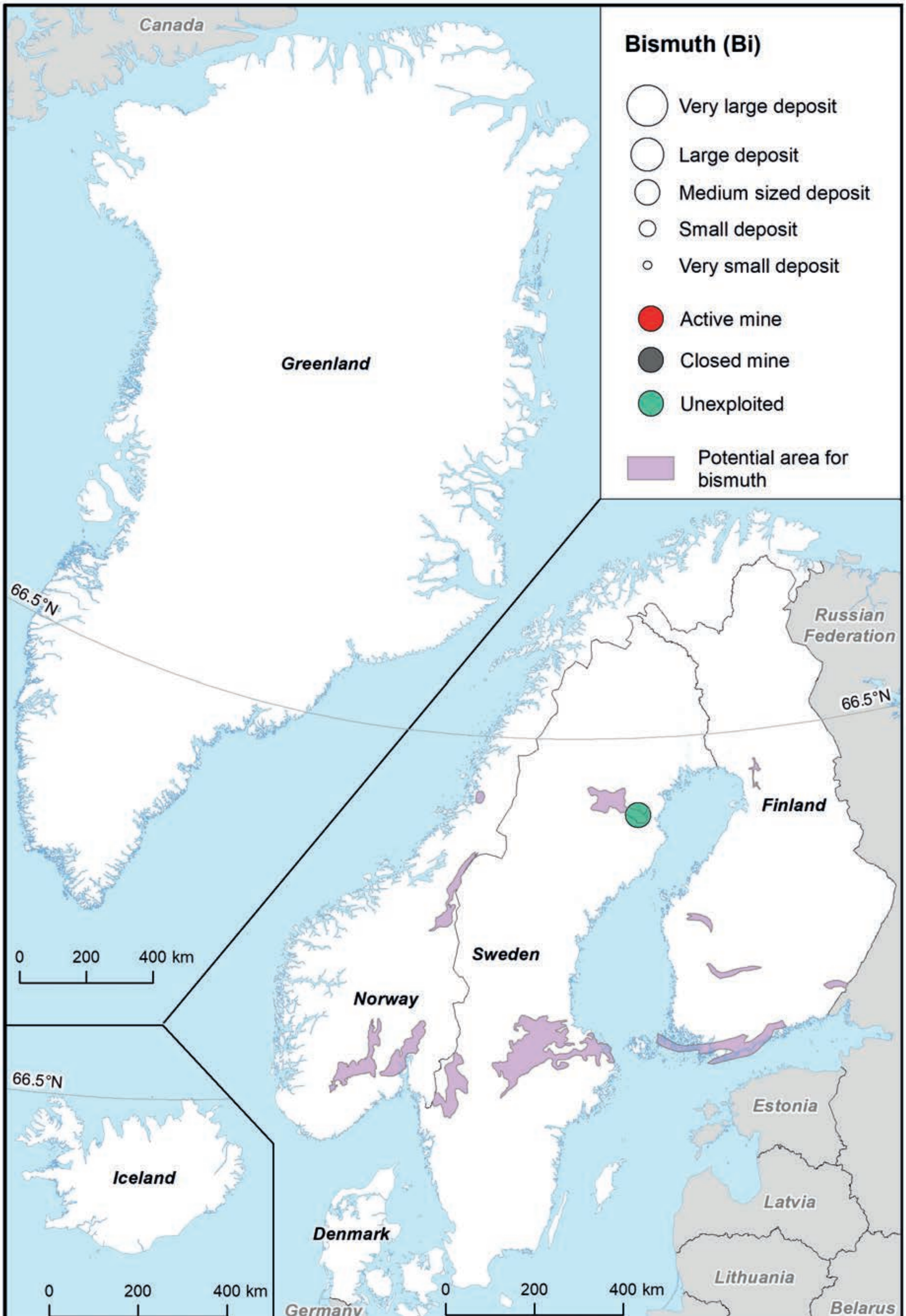

Figure 11. Locations of deposits with known bismuth resources and areas with known or assumed potential for additional bismuth resources in the Nordic countries.

3.5 Cobalt (Co)

Commodity	Cobalt (Co)	Data source
Uses of the commodity	Main uses: ***Li-ion batteries 50–60 %*** Superalloys, hardfacing, special steels and other alloys 20 % Minor uses: Catalysts for the petroleum and chemical industries; paints, varnishes, ink dye pigments, porcelain enamels; magnets and magnetic recording media Major Future uses: ***Batteries*** to fully dominate near-future Co demand, superalloys	Hund et al. (2020), Latunussa et al. (2020); Schütte (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries (tons of metal)	Mine production: 1,560 t (all from Finland). Known resources: Finland 453,500 t, Norway 11,687 t, Sweden 24,271 t. These are minimum estimates, as Co grades are not known or are only partially known for many Ni, PGE and talc deposits which contain potential by-product Co. Resource potential: Finland: 'Undiscovered resources' at regional scale estimated to 108,000 t Co. Additional potential in Talvivaara-type Ni-Zn deposits. Greenland: Several Ni-Co projects are in progress but no resource estimates on Co are available. Norway: Additional resource potential in Ni and Cu-Zn deposits. Sweden: Additional resource potential in Ni deposits.	Stensgaard et al. (2016), Rasilainen et al. (2017, 2020), Horn et al. (2021)
Global production (2020)	140,000 t Co (mine production)	USGS (2021)
Main producing countries (2019, 2020)	Mine production (USGS 2021): Democratic Republic of Congo (DRC) 68 %, Russia 4.5 %, Australia 4.1 %, Philippines 3.4 %, Cuba 2.6 %, Canada 2.3 % Refinery production (Brown et al. 2021): China 63 %, Finland 9 %, Belgium 4.8 %, Canada 4.5 %, Japan 4.3 %	USGS (2021)
Nordic refinery and smelter production (tons of metal)	Finland: 15,141 t; Norway: 4,300 t	National statistics for 2020

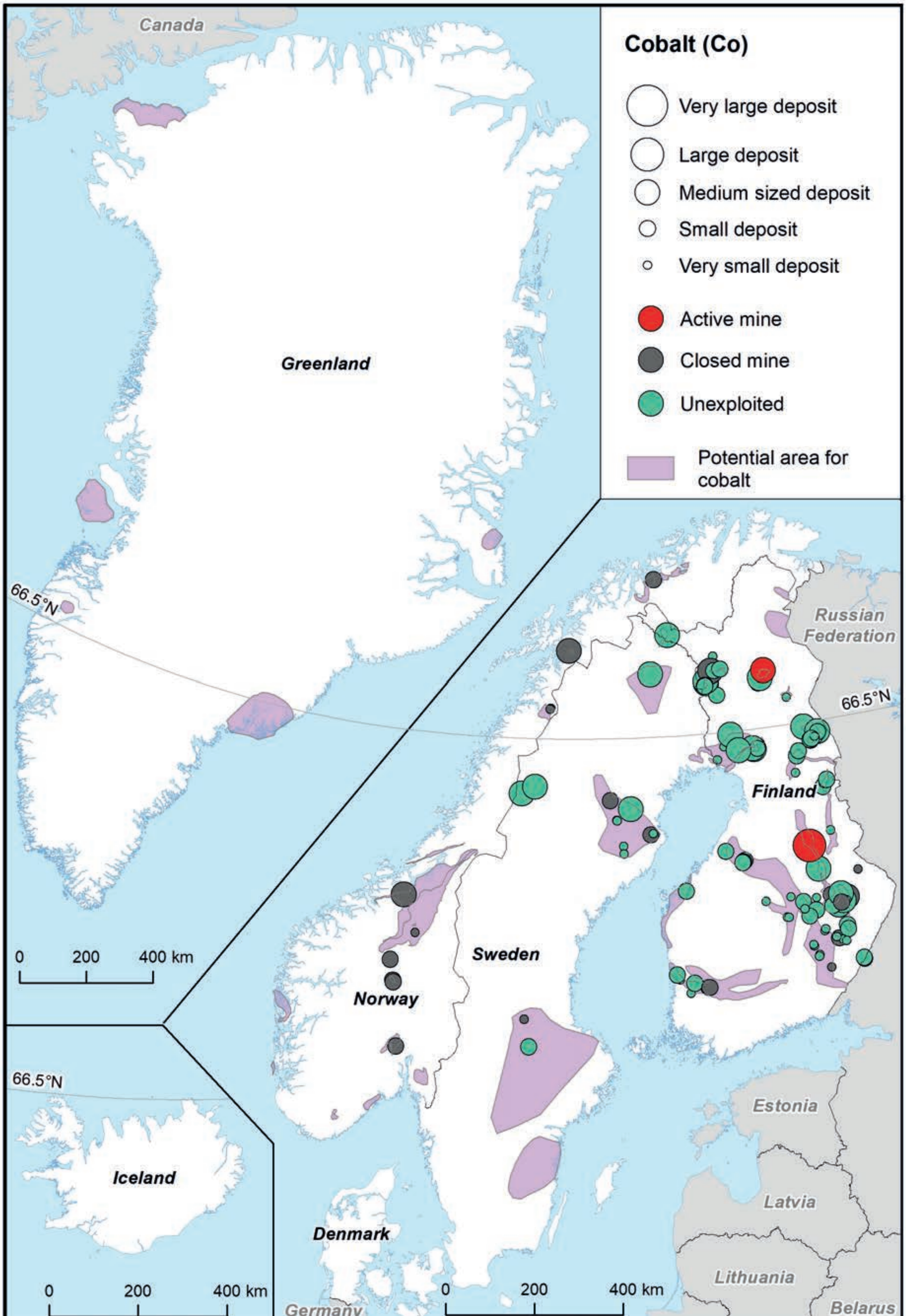

Figure 12. Locations of deposits with known cobalt resources and areas with known or assumed potential for cobalt resources in the Nordic countries.

3.6 Fluorspar (fluorite, CaF_2)

Commodity	Fluorspar (fluorite, natural CaF_2)	Data source
Uses of the commodity	Main uses: Acid and metallurgical Minor uses: Ceramic grade of fluorspar; organic synthesis; ***production of uranium hexafluoride***, the starting material for separation of uranium isotopes for making nuclear fuel. Future uses: Applications and uses of fluorspar will remain stable, except there is a major push to substitute fluorine used in many industries (especially in the air condition and refrigerator sector) for more environmentally friendly options.	Fulton & Miller (2006), Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	No Nordic production. Known resources: Greenland 250,000 t, Norway 1,160,000 t (mainly Lassedalen: 4 Mt ore at 24.6 % fluorite), Sweden 2,828,170 t (Storuman). Resource potential: Finland: No known resource potential. Greenland: At Kvanefjeld, there are large fluorine resources of a fluoride mineral (villiaumite (NaF)). Several deposits with their resources not assessed. Iceland: Very small potential for fluorspar in Breiðdalur, East Iceland. Norway: About 30 registered deposits of fluorspar Sweden: Most of the known deposits are historic closed mines from which there are no resource estimates available.	Tertiary Minerals (2012), Stensgaard et al. (2016), GME (2018), Lauri et al. (2018), Franzson, H. (pers. com. 2021)
Global production (2020)	7.6 Mt	USGS (2021)
Main producing countries (2020)	China 57 %, Mexico 16 %, Mongolia 9.5 %, South Africa 4.2 %, Vietnam 3.2 %	USGS (2021)
Nordic refinery and smelter production	None	

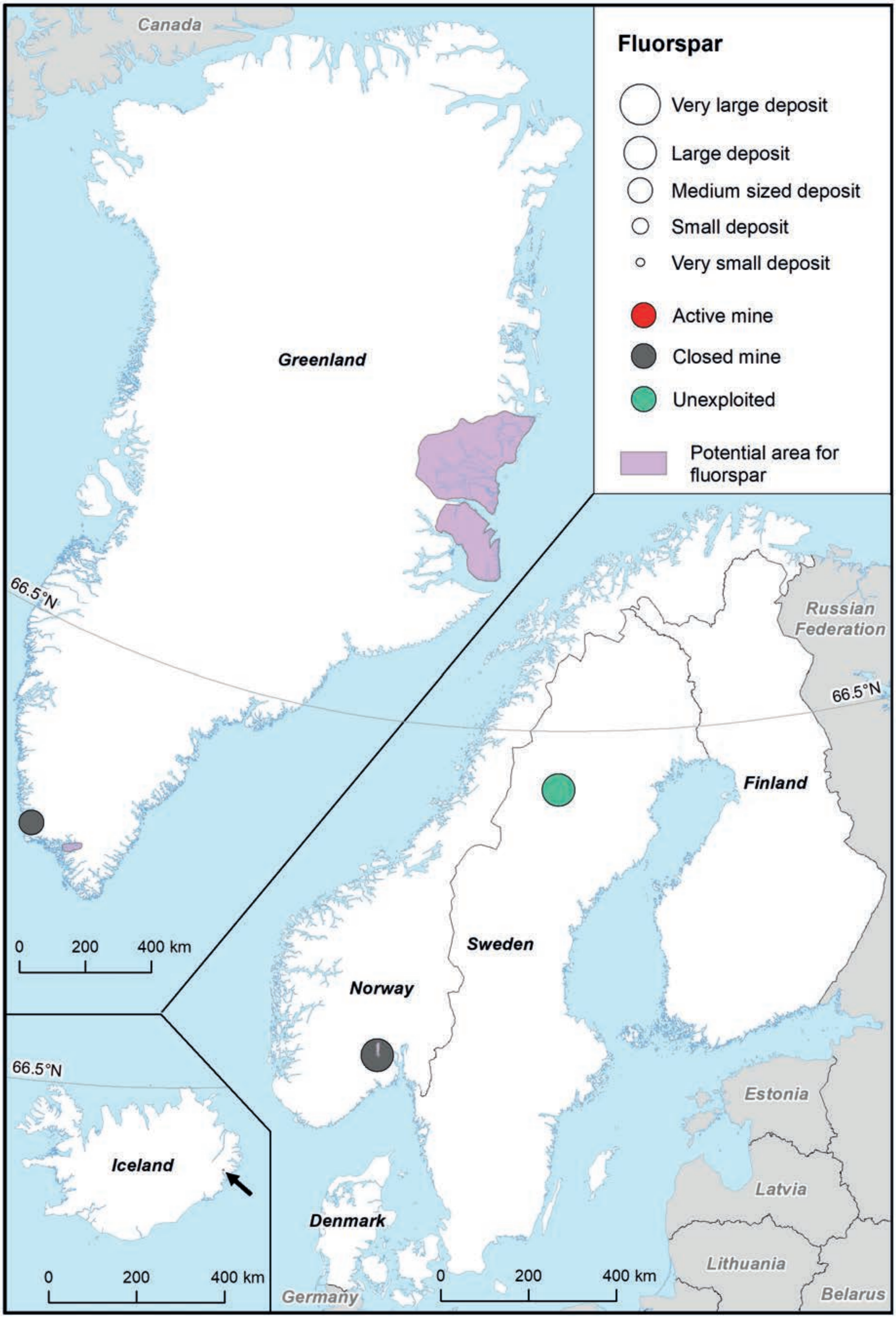

Figure 13. Locations of deposits with known fluorspar resources and areas with known or assumed potential for fluorspar resources in the Nordic countries. The associated resource-potential area in Iceland is assumed to be very small, hence indicated by a black arrow.

3.7 Gallium (Ga)

Commodity	Gallium (Ga)	Data source
Uses of the commodity	Main uses: ***Integrated circuits, LED lighting*** Minor uses: ***CIGS solar cells, displays***, low temperature melting solders and alloys, ***laser diodes***, optoelectronic devices. Future uses: ***Radio frequency devices, LED and solar cell uses expected to increase. Demand in integrated circuits expected to be steady.***	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production. There are no primary gallium ores in the Nordic countries (are very rare anywhere in the world). Known resources: Greenland 21,300 t Ga (the Skaergaard intrusion). Resource potential: Zinc-dominated sulphide ores across Fennoscandia and Greenland are possible sources, but apparently none is tested for gallium.	Stensgaard et al. (2016), Lauri et al. (2018)
Global production (2020)	300 t	USGS (2021)
Main producing countries (2020)	China 96.7 %, Russia 1.3 %, Japan 1 %, South Korea 1 %. Gallium is extracted as a by-product of aluminium production, and some is produced from the residues of zinc production.	USGS (2021)
Nordic refinery and smelter production (tons of metal)	There is a potential to produce, but apparently no recovery. Iceland: Gallium content in imported raw aluminium to refineries is estimated to be 100–120 t/a. There is a potential for extraction of Ga from bauxite being processed in Norway: Elkem had, for a short period (late 1980s), a plant aimed at production of 5 t Ga/year. In addition, there is the fly ash from coal-fired power plants as another possible source.	Alcoa Fjarðaál (2021), Norðurál (2021), Rio Tinto á Íslandi (2021)

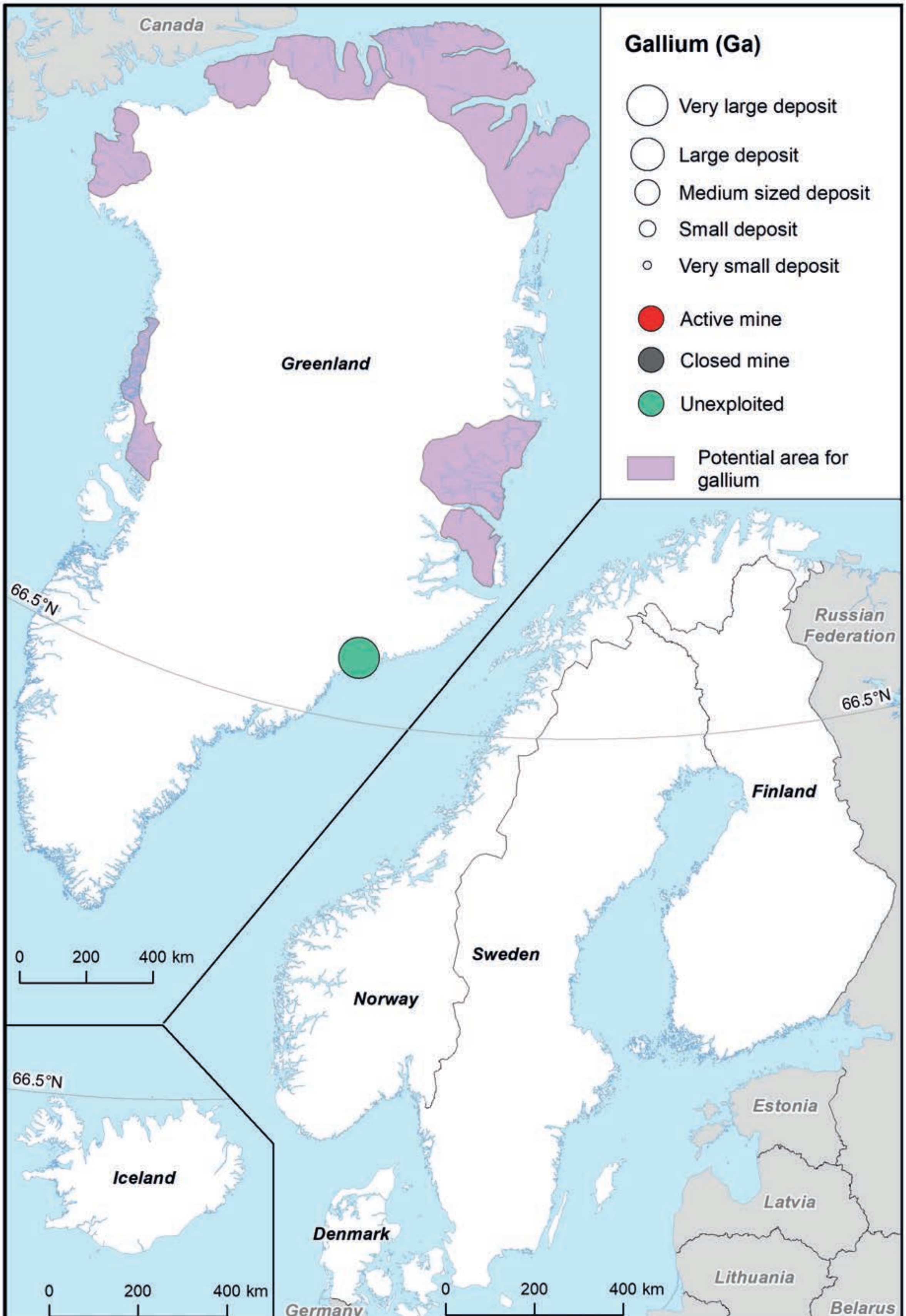

Figure 14. Locations of deposits with known gallium resources and areas with known or assumed potential for gallium resources in the Nordic countries.

3.8 Germanium (Ge)

Commodity	Germanium (Ge)	Data source
Uses of the commodity	Main uses: ***Fibre optics, infrared (IR) optics*** Minor uses: Electrical equipment, ***solar cells***, polymerisation catalysts, ***LEDs, germanium wafers*** Future uses: ***Solar cells (CIGS), IR and fibre optics***	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production. There are no primary germanium ores in the Nordic countries, nor elsewhere in Europe. Known resources: none Resource potential: Greenland: Ge is recorded from zinc occurrences in North Greenland with up to 0.05 % Ge in sphalerite. Finland, Norway, Sweden: Possibly minor potential.	Stensgaard et al. (2016), Lauri et al. (2018)
Global production (2020)	130 t (refinery production). Mine production not known.	(USGS 2021)
Main producing countries (2020)	Refinery production: China 64 %, Belgium, Canada, Germany, Japan, Russia, and Ukraine jointly 36 % (production in the latter four countries not known in detail, values are estimates). Only 12 % of germanium is mined outside of China and Russia, and relevant data is not available from these countries in any accuracy. Globally, only about 3 % of the Ge contained in zinc concentrates is recovered.	Latunussa et al. (2020), Brown et al. (2021), USGS (2021)
Nordic refinery and smelter production (tons of metal)	Presently none. Germanium was extracted from leaching of zinc refinery residues in Finland, from imported ore in significant amounts, up to 2015 when 13 t of Ge was produced from imported raw materials. Since 2016, Ge production in Finland has been minimal.	

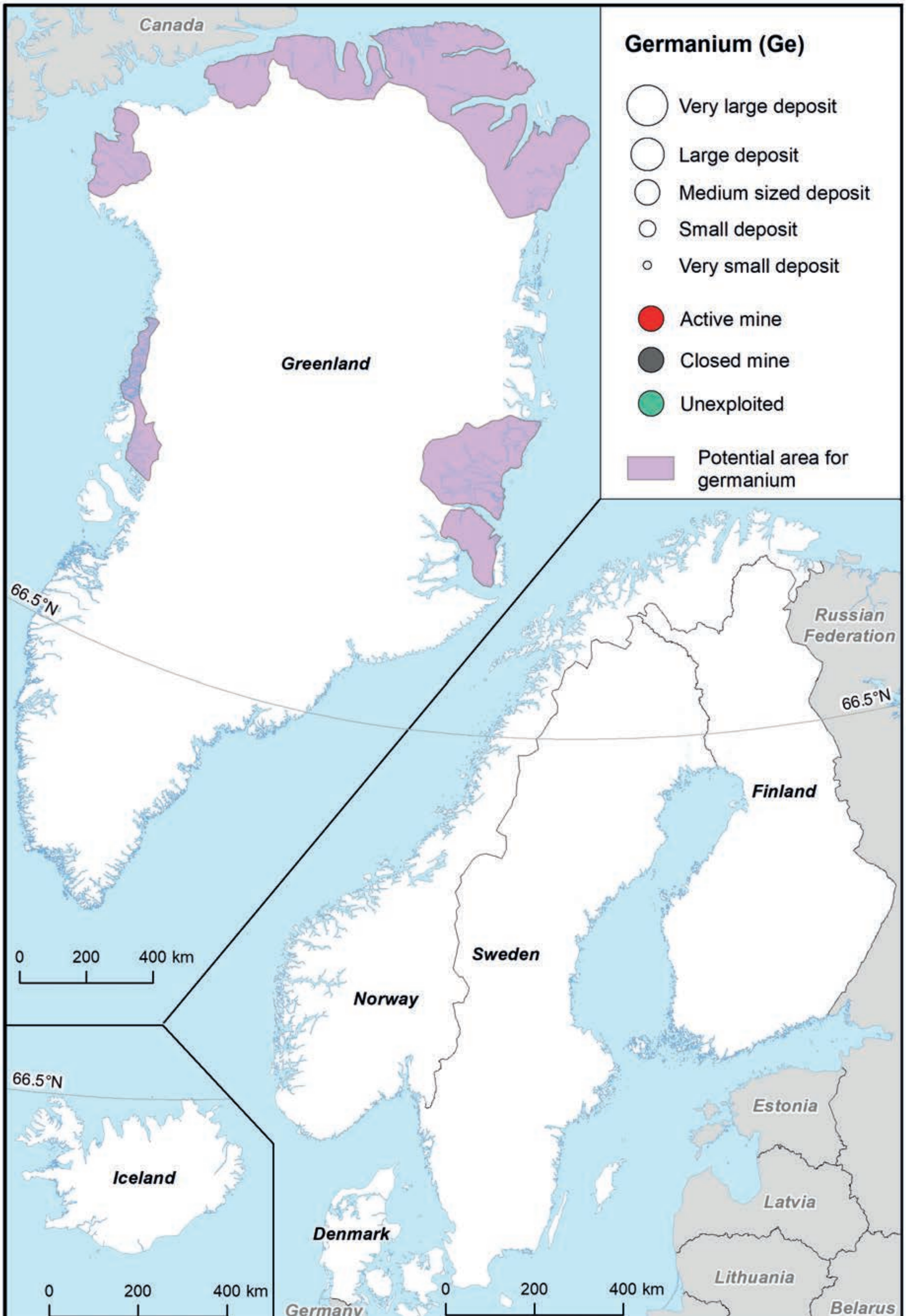

Figure 15. Locations of deposits with known germanium resources and areas with known or assumed potential for germanium resources in the Nordic countries.

3.9 Graphite (C)

The industry classifies natural graphite into three main groups a) flake graphite b) amorphous graphite and c) vein graphite. Flake graphite makes up about 58 % of world production. Li-ion batteries demand "spherical shaped" graphite particles that are produced by a specialised grinding, chemical purification and coating of the graphite sphere of otherwise high-quality natural graphite. For all graphite deposits, it is the flake size and carbon content that determine the price and end use of the produced graphite concentrate.

Commodity	Graphite (C)	Data source
Uses of the commodity	Main uses: ***Electrodes***, foundry industry, refractory materials, metallurgical industry. ***Li-ion batteries***. Carbon brushes. Minor uses: Shapes, friction products, lubricants, pencils Future uses: Refractories for the steel industry assumed as the dominant market. ***Battery use to dominate the demand. Forecasted demand increase: large-scale fuel cells, modular nuclear reactors (PBNRs), and vanadium redox batteries.***	Hund et al. (2020), Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production: Norway 16,000 t (Europe's only producer of flake graphite). Known resources: Finland 1,276,900 t, Norway 17,985,000 t, Sweden 10,500,766 t, Greenland 890,000 t. Resource potential: Finland: Several flake graphite and extensive amorphous graphite occurrences, probably contain several Mt of graphite. Greenland: Historic mine production and known resources suggest additional major potential. Norway: About 70 registered graphite occurrences in four main graphite provinces Sweden: At least eight graphite deposits and occurrences are known.	Stensgaard et al. (2016), Talga Resources (2017), Lauri et al (2018), Thrane & Kalvig (2018), Beowulf Mining (2019), Gautneb et al. (2020a), Gautneb et al. (2020b), Leading Edge (2021)
Global production (2020)	1.1 Mt	USGS (2021)
Main producing countries (2020)	China 60 %, Mozambique 10.9 %, Brazil 8.6 %, Madagascar 4.3 %	USGS (2021)
Nordic refinery and smelter production (tons of metal)	Norway: 16,000 t/a	National statistics for 2020

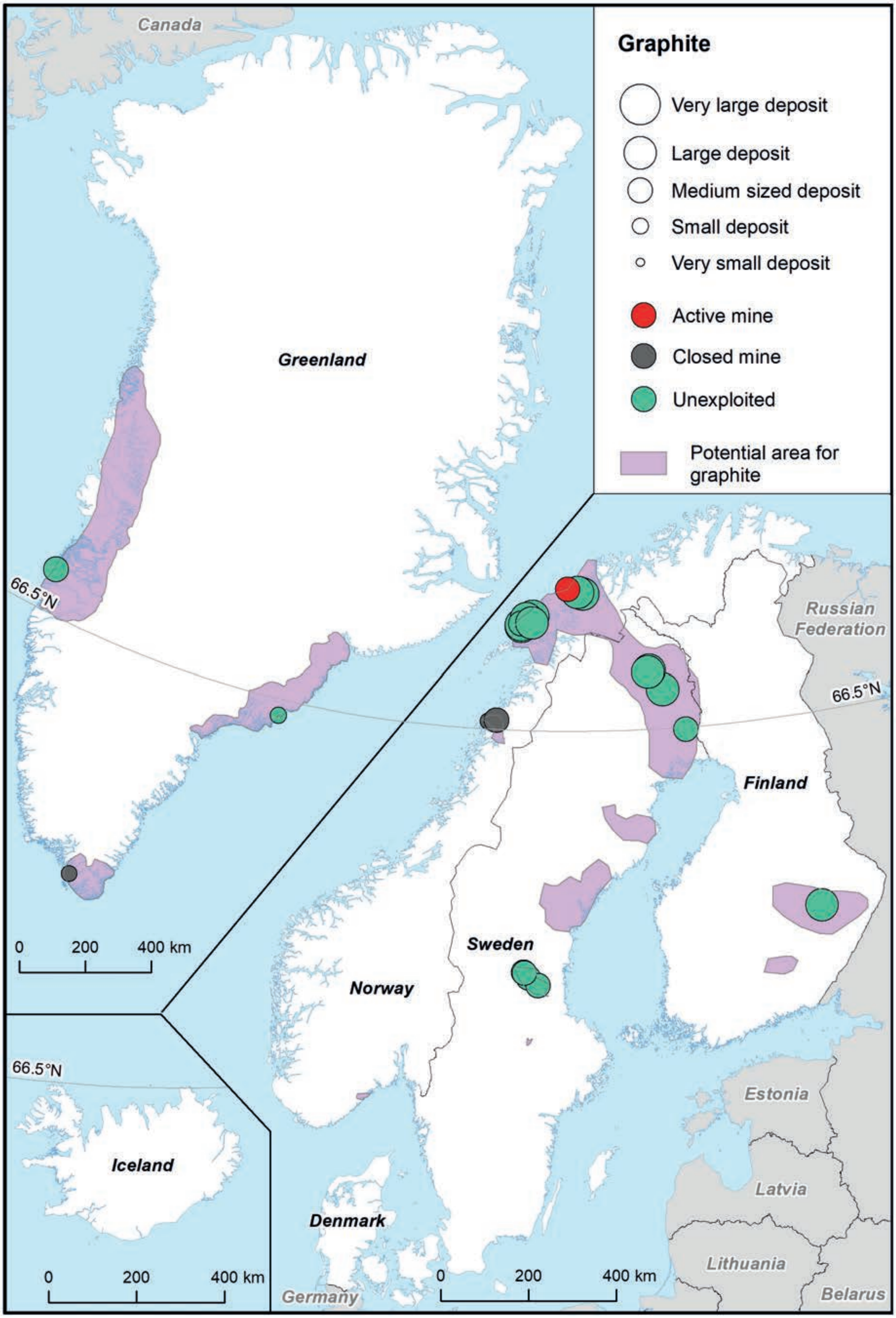

Figure 16. Locations of deposits with known graphite resources and areas with known or assumed potential for graphite resources in the Nordic countries.

3.10 Hafnium (Hf)

Commodity	Hafnium (Hf)	Data source
Uses of the commodity	Main uses: Super alloys 60 %, plasma cutting 15 % Nuclear rods 10 % Minor uses: Catalysts, optical use, blue lasers, semiconductors Future uses: Current main uses assumed to remain the most significant with nuclear and aerospace uses increasing. In addition, ***solar cells (CIGS), IR and fibre optics,*** thermoelectric materials, radiative cooling materials, radiation oncology.	BRGM et al. (2017), Latunussa et al. (2020)
Mine production, resources and additional resource potential in the Nordic countries	No mine production nor known global resources. There are no primary hafnium ores in the Nordic countries or elsewhere in the world. Known resources: Greenland 1,100,000 t, Sweden 6,781 t. Resource potential: Finland: A potentially large resource at Sokli. Greenland, Norway, Sweden: Potential in all zirconium-rich mineral resources.	Short et al. (2015), Lauri et al. (2018), Latunussa et al. (2020), Tanbreez (2021), Stensgaard et al. (2016)
Global production (2020)	About 70 t (refinery production, exact data not available as the trade is not transparent). Production of Hf-free zirconium is the main source for Hf. Mine production not known (all Hf is recovered from zirconium ores).	Ecclestone (2020), Latunussa et al. (2020), USGS (2021)
Main producing countries (2020)	Refined Hf: France 50 %, USA 44 %, China 3 %, Russia 3 %	Ecclestone (2020), Latunussa et al. (2020)
Nordic refinery and smelter production (tons of metal)	None	

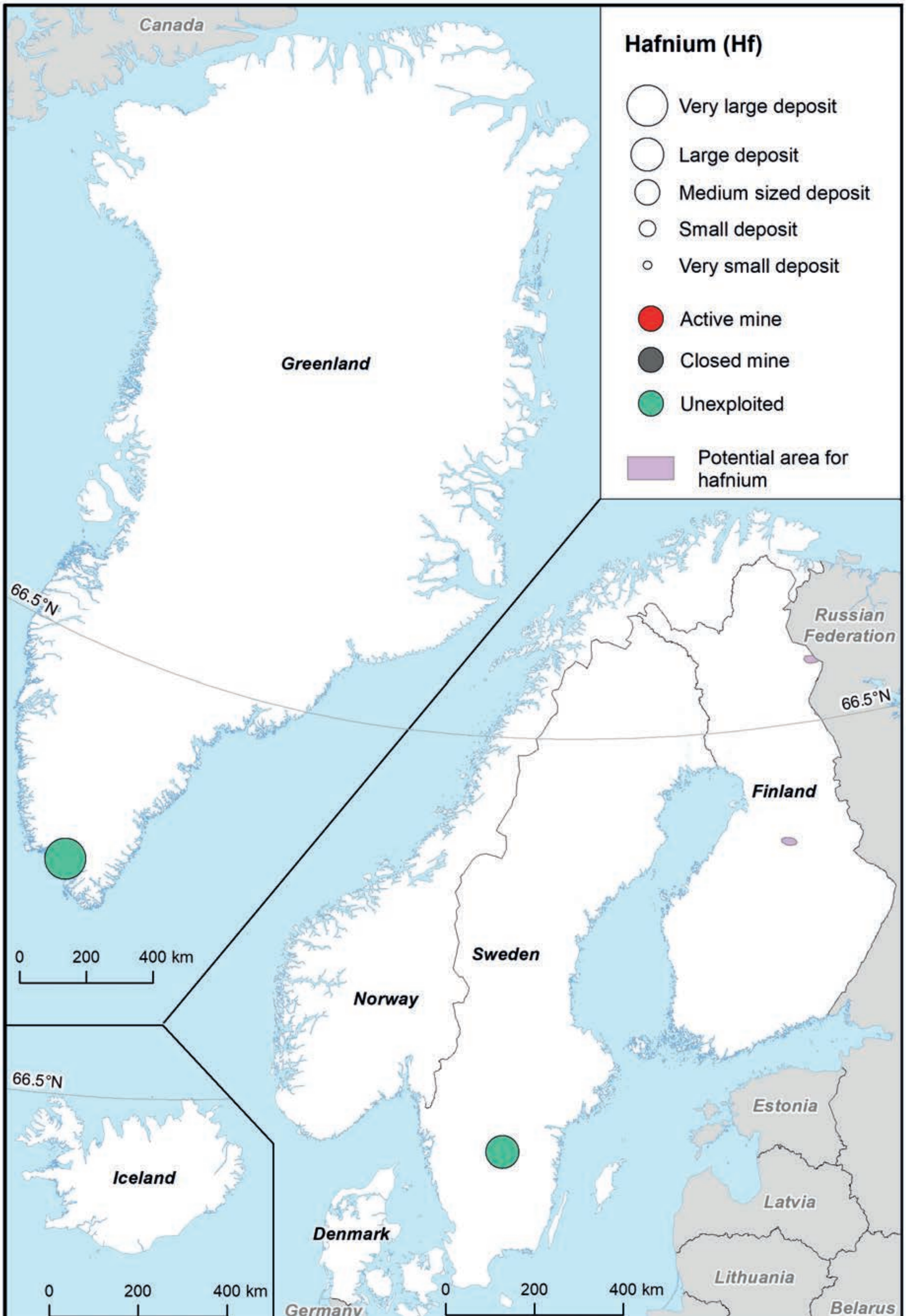

Figure 17. Locations of deposits with known hafnium resources and areas with known or assumed potential for hafnium resources in the Nordic countries.

3.11 Indium (In)

Commodity	Indium (In)	Data source
Uses of the commodity	Main uses: Electronics (flat screens, touch panels), low temperature solder alloys, ***CIGS PV cells*** (thin films in solar panels), glass and windscreens Minor uses: Light emitting diodes ***(LEDs) and laser diodes,*** other semi-conductor uses, ***batteries*** Future uses: Given the use of indium in ***PV cells***, it has a role in the green energy transition	Mudd et al. (2017), Werner et al. (2017), Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production nor known resources. There are no known primary indium ores in the Nordic countries; such ores are globally rare. Resource potential: Trace amounts of indium are found in base metal ores, particularly in zinc ores. The potential resources of indium in zinc-rich massive sulphide deposits in Fennoscandia and Greenland are possibly large, but figures for the indium content are generally missing and more data are needed.	Jonsson et al. (2013), Werner et al. (2015, 2017), Stensgaard et al. (2016), Mudd et al. (2017), Latunussa et al. (2020)
Global production (2020)	900 tons In metal from primary refinery production. Indium can be, but is not commonly, recovered during the smelting process.	USGS (2021)
Main producing countries (2020)	Mine production figures are not known. Refinery production: China 56 %, South Korea 22 %, Japan 7 %, Canada 6 %, France 6 %, Belgium 2 %.	USGS (2021)
Nordic refinery and smelter production	None	

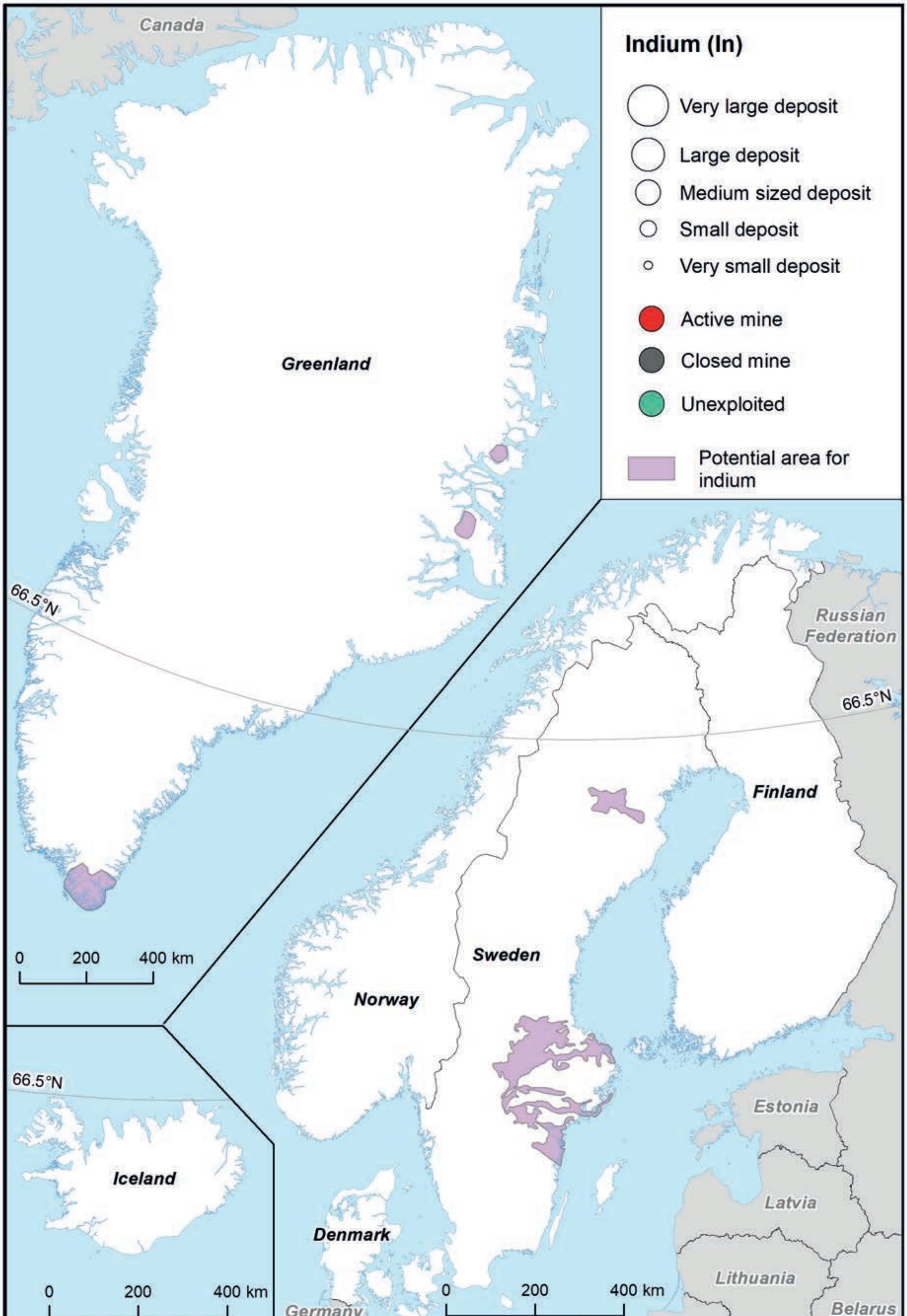

Figure 18. Locations of deposits with known indium resources and areas with known or assumed potential for indium resources in the Nordic countries.

3.12 Lithium (Li)

Commodity	Lithium (Li)	Data source
Uses of the commodity	Main uses: ***Batteries***, ceramics and glass, lubricating greases, continuous casting, flux powders Minor uses: Air treatment, polymer production, primary aluminium production, rubber and thermoplastics, light-weight metal alloys, pharmaceuticals, drilling mud Future uses: ***Lithium metal–air battery***, Li-Mg alloys. ***electric vehicle battery demand on strong increase***. Other uses remain stable.	Warren (2016), USGS (2021)
Mine production, resources and additional resource potential in Nordic countries	No mine production in Nordic countries. Known resources: Finland 74,790 t, Greenland 210 t, Sweden 3,240 t. Resource potential: Finland: 'Undiscovered resources' at regional scale estimated to 510,000 t. Greenland: Resource potential is much higher than what the known resources suggest. Iceland: unknown. Norway: unknown. Sweden: Potential resources probably reasonably large but no assessments been done.	Kunzendorf et al. (1982), Rasilainen et al. (2018), FODD (2020), Gautneb et al. (2020a), Gautneb et al. (2020b)
Global production (2020)	82,000 t, calculated to lithium metal (not lithium oxide)	USGS (2021)
Main producing countries (2020)	Australia 49 %, Chile 22 %, China 17 %, Argentina 7.6 %	USGS (2021)
Nordic refinery and smelter production	None	

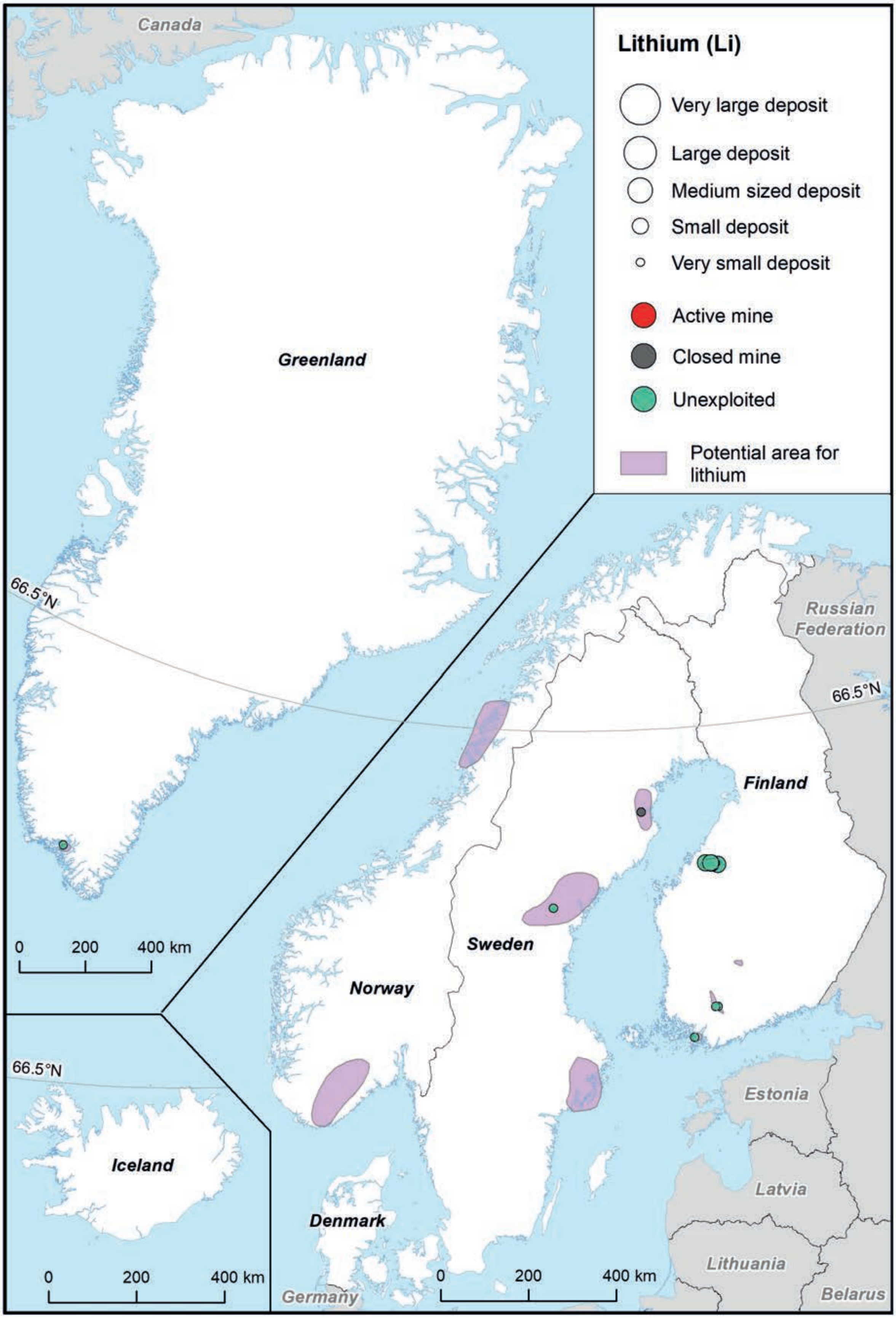

Figure 19. Locations of deposits with known lithium resources and areas with known or assumed potential for lithium resources in the Nordic countries.

3.13 Niobium (Nb)

Commodity	Niobium (Nb)	Data source
Uses of the commodity	Main uses: Steels (90 %), e.g. HSLA steel which is used in oil and gas pipelines, bridges and other infrastructure, ship hulls, aircrafts and automobiles Minor uses: ***Superalloys in power generators, turbines*** and jet engines. Hard-cutting tools, chemicals, special glass, acoustic wave filters, ***super-conducting magnets***. Future uses: Demand is driven by steel production. Niobium additive decreases the amount of steel needed in the transport sector and can boost energy efficiency due to ***lighter-weight components***.	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in Fennoscandia	No production Known resources: Finland: 123,000 t, Greenland 6,467,000 t, Norway 22,000 t. Resource potential: Finland: A large potential in the Sokli deposit Greenland: Additional major potential Norway: Moderate to major potential Sweden: Potential exists in several types of mineral deposits.	Stensgaard et al. (2016), Thrane (2016), FODD (2020), Tanbreez (2020)
Global production (2020)	78,000 t Nb	USGS (2021)
Main producing countries (2020)	Brazil 91 %, Canada 8 %	USGS (2021)
Nordic refinery and smelter production	None	

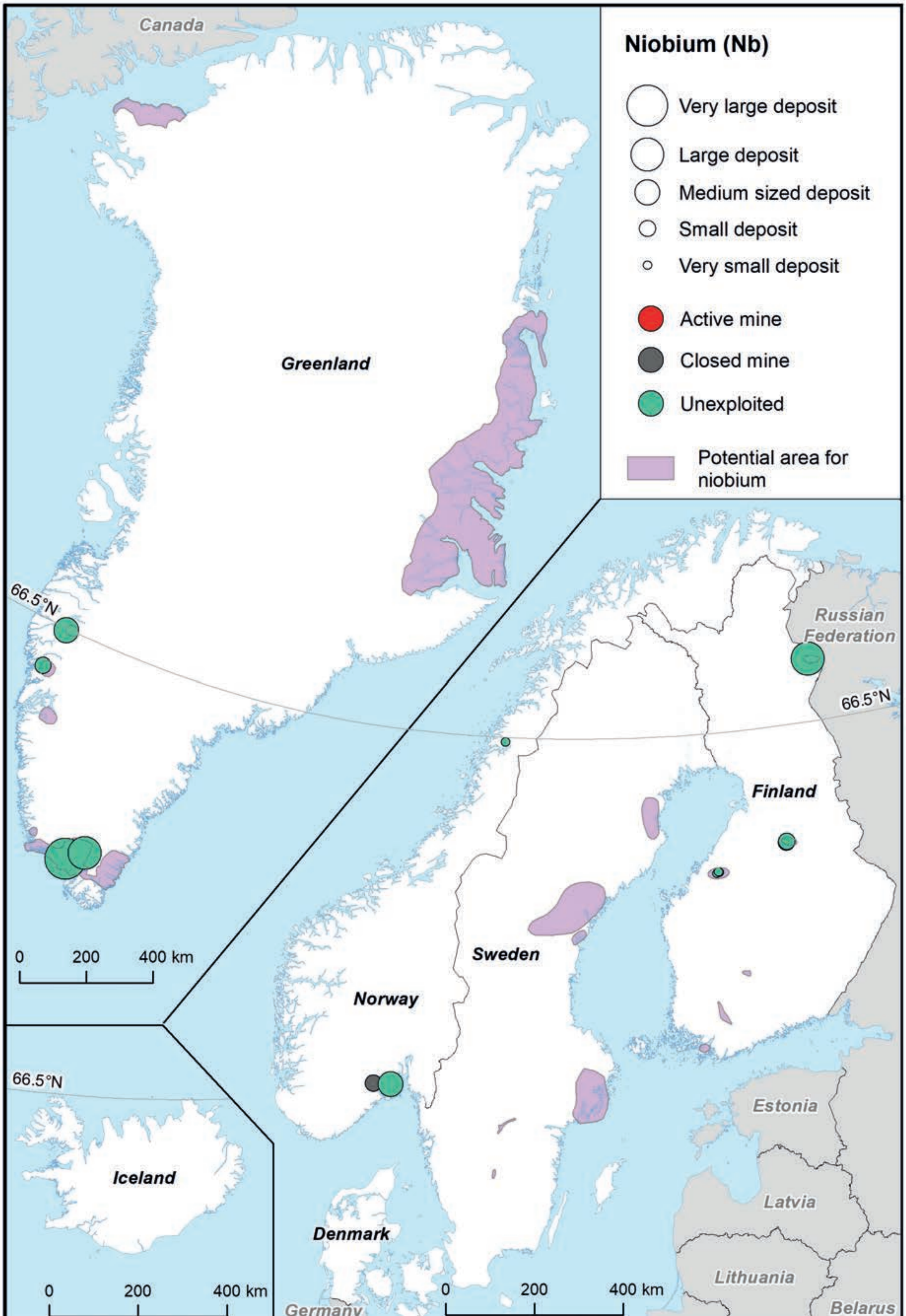

Figure 20. Locations of deposits with known niobium resources and areas with known or assumed potential for niobium resources in the Nordic countries.

3.14 Phosphate rock and Phosphorus (P)

Note that all figures below given in phosphorus content (P) – not in P_2O_5.

Commodity	Phosphorus (Phosphate)	Data source
Uses of the commodity	Main uses: Fertilisers (90 %) Minor uses: Metallurgic industry, electronics, pyrotechnics, organic synthesis, feed for livestock, cleaning and fire-resistant substances, insecticides, herbicides Future uses: Fertilisers to remain the by far dominant use, with a demand in a constant increase directly linked to human population growth. ***Use in batteries and electronics is assumed to increase*** but remain minor compared to the demand in fertilisers.	Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production: 182,600 t phosphorus (P, Finland) Known resources: Finland: 219 Mt, Greenland: 358,000 t, Norway: 14 Mt, Sweden: 26.9 Mt P. Resource potential: Finland: Currently under assessment Greenland: Large potential Norway: Some potential, not assessed Sweden: Large potential in past and presently mined iron deposits and in phosphorite rocks in Caledonian and Cambrian shales	Gustafsson (1979), Knudsen (1991), Lauri et al. (2018), FODD (2020)
Global production (2020)	223 Mt of phosphate rock (equals to 29.4–41.2 Mt P)*. About 0.5 % of mined phosphorus is refined to elemental P.	Latunussa et al. (2020), USGS (2021)
Main producing countries (2020)	China 40 %, Morocco and West Sahara 17 %, United States 11 %, Russia 6 %	USGS (2021)
Nordic refinery and smelter production	Not relevant	

* No accurate phosphorus content is available of the 'phosphate rock' in the global statistics, as the grade varies, and companies and countries commonly do not disclose the details.

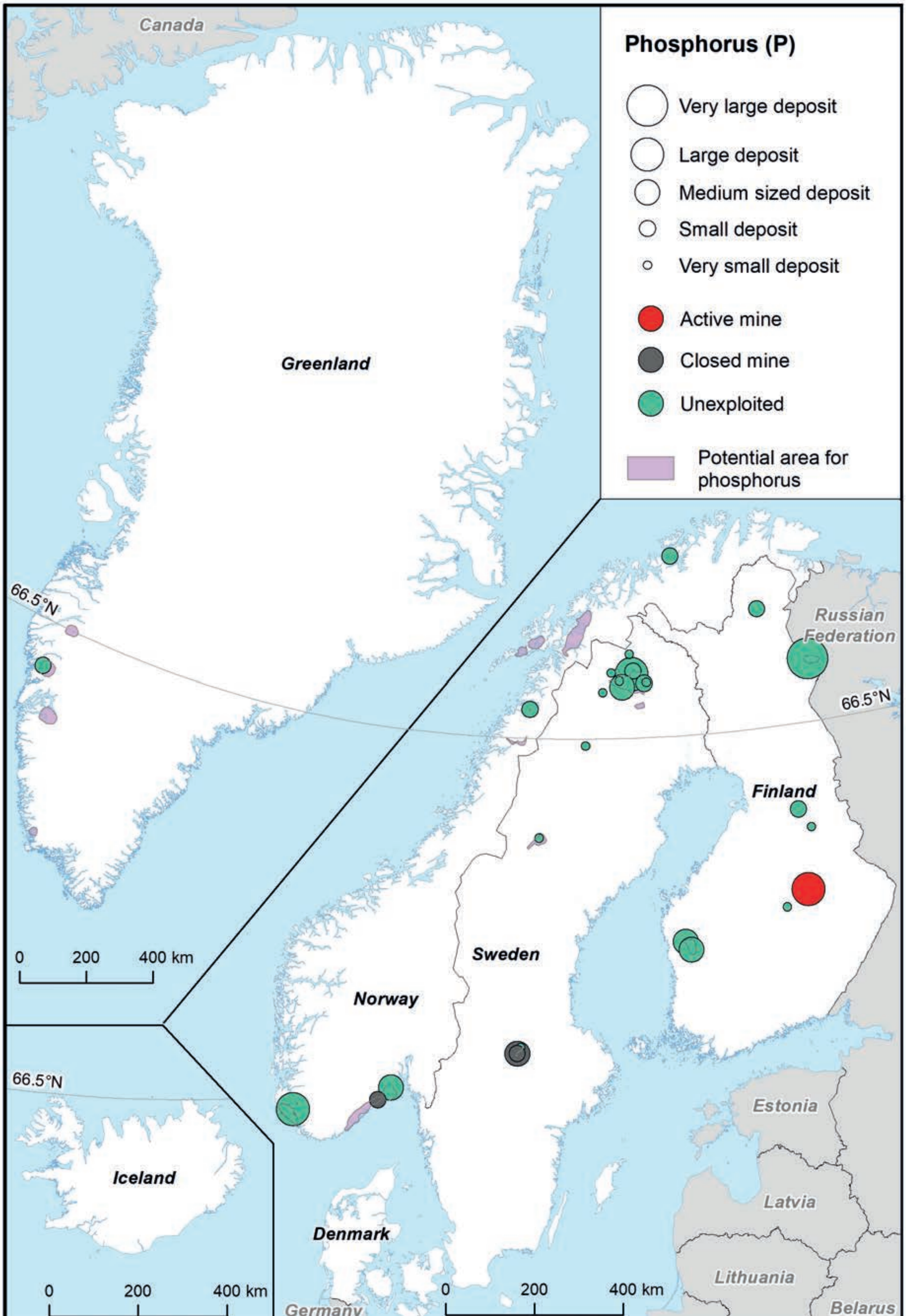

Figure 21. Locations of deposits with known phosphorus resources and areas with known or assumed potential for phosphate resources in the Nordic countries.

3.15 Platinum Group Metals (Pt, Pd, Rh, Ru, Ir, Os)

Platinum group metals include the six metals indicated above, of which platinum (Pt) and palladium (Pd) are most common and their production is tenfold compared to other PGMs. Pt, Pd and also rhodium (Rh) are important as vehicle exhaust catalysts. Osmium has little technical usage and some Os compounds are highly toxic.

Commodity	Platinum group metals (PGM/PGE) = Pd, Pt, Rh, Ir, Ru, Os	Data source
Uses of the commodities	Main uses: ***Vehicle exhaust catalysts***, jewellery, investment. ***Electronics industry (half of the Ir and Ru demand).*** Crucibles for growing single crystals for lasers, scanners, ***LEDs***, and for surface acoustic wave filters; OLED screens; thermostats and relays, hard disk drives, electrical contacts. Future uses: ***Fuel cells, super conductors. Exhaust catalyst use*** (Pd, Pt, Rh) growing in short term, but may significantly decrease if electric cars take a major share in the vehicle production. On the other hand, if the ***fuel cell and hydrogen power technology*** grows, the PGE demand will do so accordingly. Demand in electronics will remain significant or grow substantially for all PGMs. For Pd, there may be significant growth in the chemical industry, in micro-electric capacitors and in seawater desalination.	Lauri et al. (2018), Johnson Matthey (2020), Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production: 858 kg Pd, 1,277 kg Pt (Finland) Known resources: Finland 856 t, Greenland 293 t, Norway 0.954 t, Sweden 0.485 t. These figures are minimum estimates, as the PGM grades are not known for many Ni and talc deposits which contain potential byproduct PGMs. For Ir, Rh, Ru and Os, there is scant information. Resource potential: Finland: 'Undiscovered resources' at regional scale estimated to 12,000 t Pd and 5,600 t Pt. Greenland: Several PGM projects but resources not estimated. Norway and Sweden: Minor potential.	Stensgaard et al. (2016), Rasilainen et al. (2017), Boliden (2020), Platina Resources (2021)
Global production	Mine production: 210 t Pd (2020), 170 t Pt (2020), 23 t Rh (2018), 7.3 t Ir (2018), 30.5 t Ru (2018)	Johnson Matthey (2020), USGS (2021)
Main producing countries, mine production (2018–2020)	Palladium (Pd): Russia 41 %, South Africa 32 %, Canada 8 %, USA 7 %, Zimbabwe 6 % Platinum (Pt): South Africa 69 %, Russia 13 %, Zimbabwe 9 %, Canada 6 % Rhodium (Rh): South Africa 80 %, Russia 12 %, Zimbabwe 5 %; Iridium (Ir): South Africa 92 %; Ruthenium (Ru): South Africa 93 %	Johnson Matthey (2020), USGS (2021)
Nordic refinery and smelter production	Recovered in Finland and Sweden, but no metal production data are available	

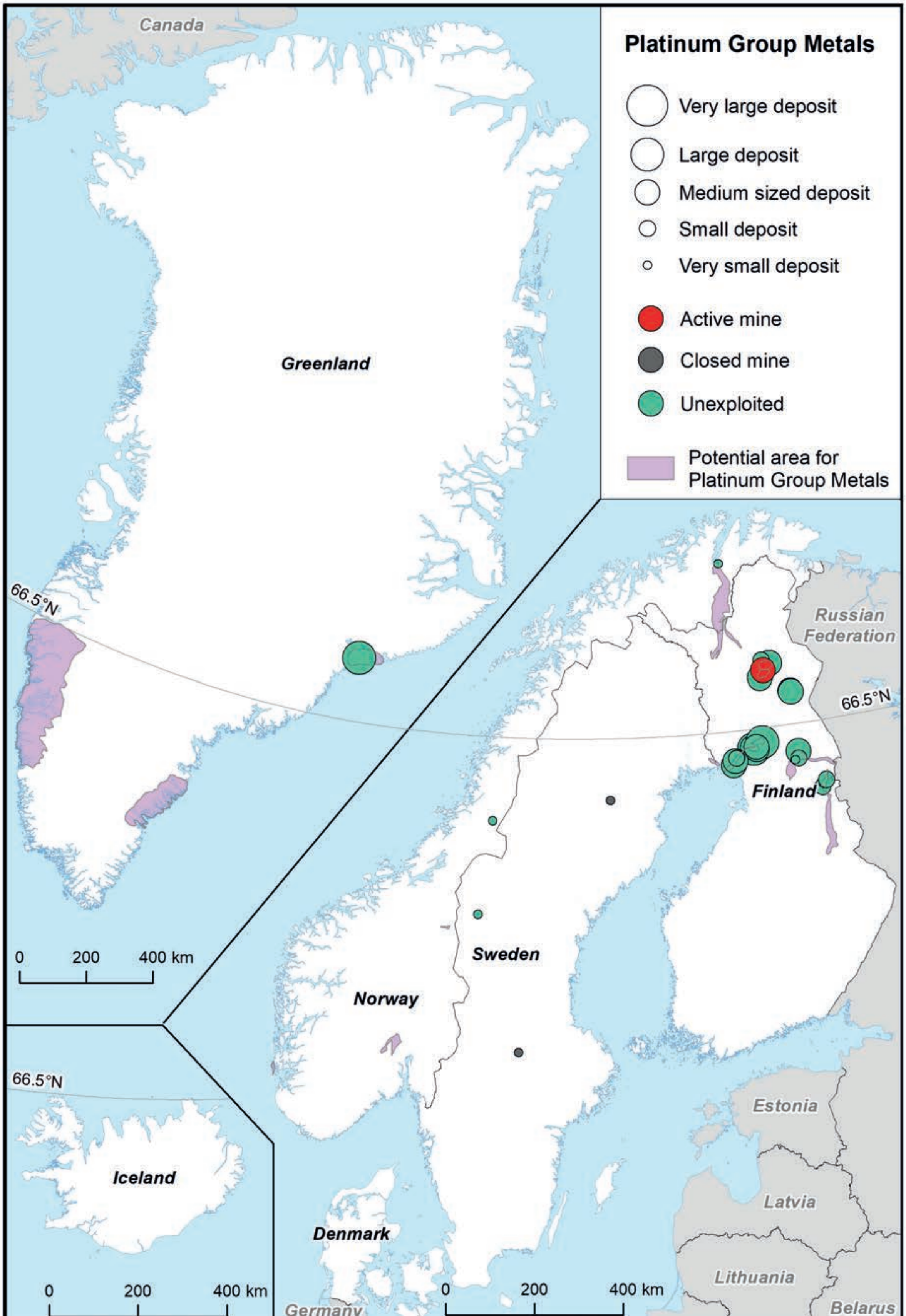

Figure 22. Locations of deposits with known platinum group metal (PGM) resources and areas with known or assumed potential for PGM resources in the Nordic countries.

3.16 Rare Earth Elements (REE)

In geological terms, the rare earth elements (REE) comprise yttrium (Y) and the Lanthanide Group of the periodic table of elements (lanthanum to lutetium). These are mostly separated into two main groups, the HREE (heavy rare earth elements; Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, together with Y), and the LREE (light rare earth elements, La, Ce, Pr, Nd, and Sm). Typically, all REEs occur in all REE-bearing deposits, but in very variable proportions, depending on the geological process that formed a particular deposit. As both the overall abundances and prices of individual REEs vary substantially, the specific contents of the more sought-after ones (such as neodymium (Nd), dysprosium (Dy) or samarium (Sm)) are important factors in determining the economic potential of a REE deposit.

Commodity	Rare Earth Elements (REE = La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y)	Data source
Uses of the commodity	Main uses: Catalysts, ***magnets***, alloys Minor uses: ***Batteries***, steel, glass and polishing, ceramics Future uses: Nearly all current uses remain significant. ***Increasing demand in, at least: fuel cells, superconductors, batteries, and magnets in electric motors in vehicles and wind turbines***	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No mine production. Known resources: Finland: 51,700 t, Greenland: 34,792,000 t, Norway: 611,300 t, Sweden: 211,000 t REE. Resource potential: Finland: Additional potential is large, currently under assessment Greenland: Several deposits with additional REE potential Norway: Some potential for additional resources Sweden: Additional potential is large and also includes apatite-iron oxide ores and related mine tailings	Gustafsson (1979), Hudson (2012), Paulick et al. (2015), Short et al. (2015), Steenfelt et al. (2016), Stensgaard et al. (2016), Al Ani et al. (2018), Andersson et al. (2018), GME (2018) Jonsson et al. (2019), FODD (2020)
Global production (2020)	206,400 t REE metals	USGS (2021)
Main producing countries (2020)	Mining: China 58 %, USA 16 %, Burma 12.5 %, Australia 7.1 %. Refining + smelting: China 85 %, Malaysia 14 %.	IEA (2021), USGS (2021)
Nordic refinery and smelter production	None	

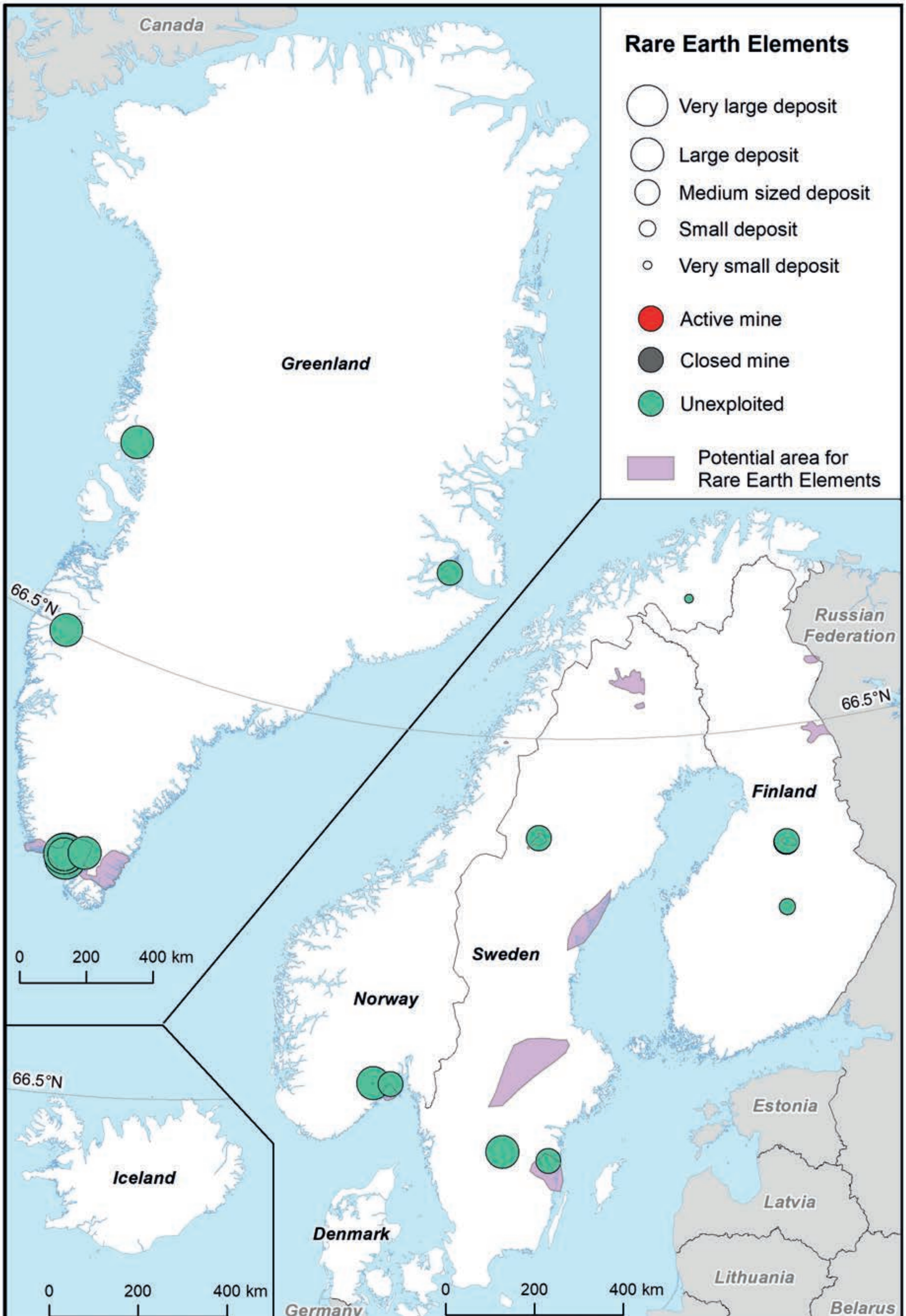

Figure 23. Locations of deposits with known rare earth element (REE) resources and areas with known or assumed potential for REE resources in the Nordic countries.

3.17 Scandium (Sc)

Commodity	Scandium (Sc)	Data source
Uses of the commodity	Main uses: ***Solid-oxide fuel cells 90 %,*** aluminium-scandium alloys 9 % Minor uses: Electronics, lasers, ***lighting***, and radioactive isotopes. Future uses: Al-Sc alloys, ***fuel cells***, electronics	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No current mine production. Known resources: Finland 2,180 t, Norway 50,000 t – these figures are a minimum estimate, as Sc grades are not known for almost all of the Nordic Nb, REE, and P deposits some of which might contain recoverable Sc. Resource potential: Finland: Possible potential in REE and P deposits. Greenland: The Kvanefjeld REE-U-Zn-F deposit has potential for scandium. Norway: Possible potential in Nb, REE and P deposits. Sweden: Only minor known Sc occurrences.	Hokka & Halkoaho (2016), FODD (2020), Resource Global Network
Global production (2016–2020)	15–25 t, exclusively as a byproduct from processing of various ores and recovered from previously processed tailings or residues.	Williams-Jones & Vasyukova (2018), USGS (2021)
Main producing countries (2016–2020)	China (60–90 %?), Russia, Philippines. Production and trade of Sc are not transparent, so production figures and trade within and between countries are uncertain.	Latunussa et al. (2020), USGS (2021), Wang et al. (2021)
Nordic refinery and smelter production	No production	

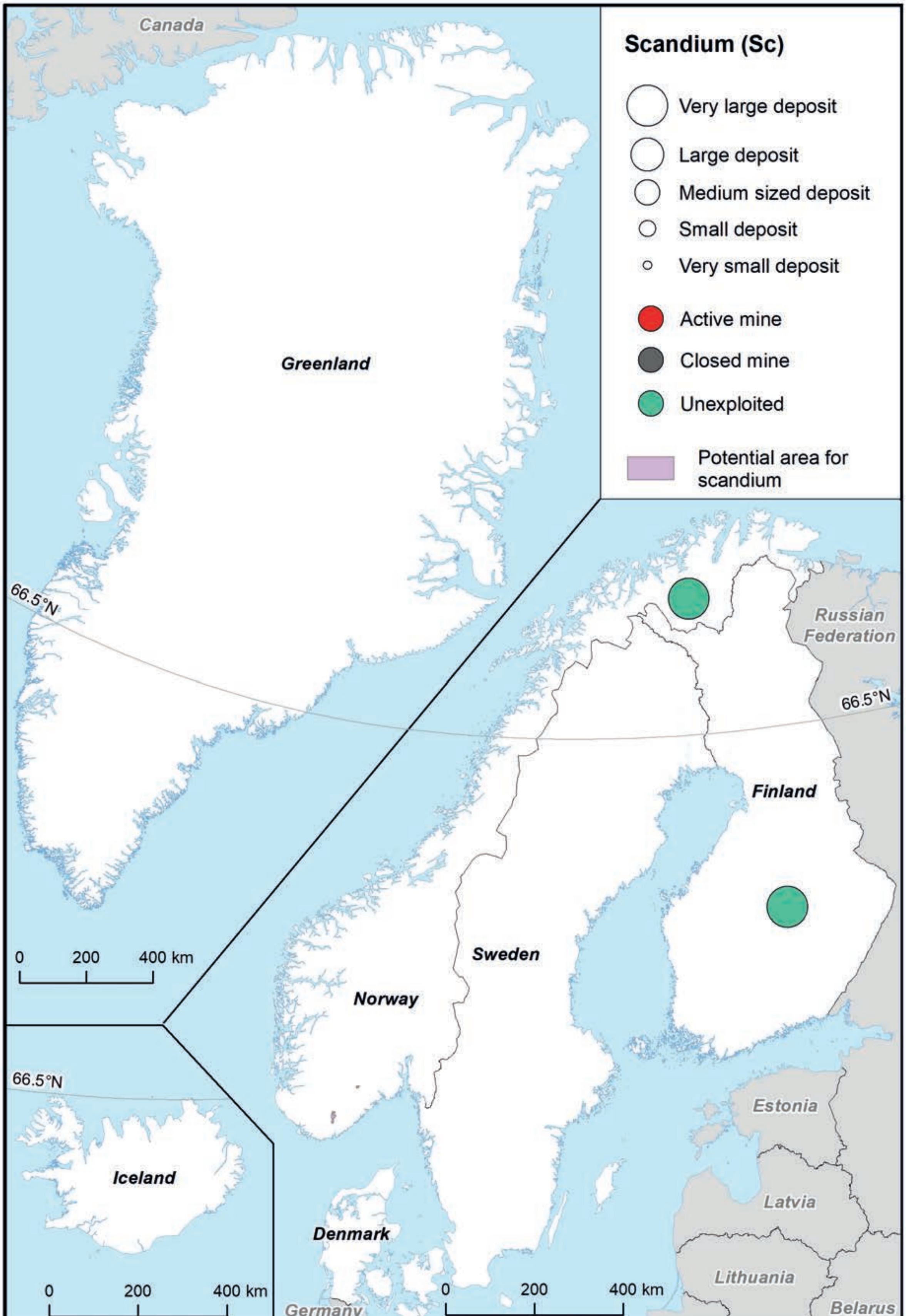

Figure 24. Locations of deposits with known scandium resources and areas with known or assumed potential for scandium resources in the Nordic countries.

3.18 Silicon Metal (Si)

Silicon metal (Si) is the elemental form of pure silicon and, like aluminium, it does not occur as a pure metal in nature. Silicon metal is produced from pure quartz (SiO_2) in dedicated smelters, in a very energy demanding production. Access to (cheap) electricity is the most important component.

Commodity	Silicon metal (Si)	Data source
Uses of the commodity	Main uses: The main use of Si metal is for the production of silicon and silane chem icals, and aluminium and iron alloys Minor uses: ***Solar photovoltaic applications, semiconductors*** Future uses: ***Photovoltaic and semiconductor demand assumed to increase most. Silicon anodes in batteries.*** Other demand assumed to be stable.	Latunussa et al., (2020), USGS (2020)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production: 240,000 t (Norway). Known resources: Greenland 2.8 Mt; Norway 28.3 Mt; Sweden 0.5 Mt. Resource potential: Finland: A large number of small occurrences with at least some having a potential for high-purity quartz, but none with a resource estimate. Greenland: Potential for quartz deposits but lack of information concerning the purity. Norway: Extensive additional potential across the country. Sweden: Major potential in parts of Sweden.	Nordic Mining (2017), Lauri et al. (2018), Eclipse (2021)
Global production (2020)	8 Mt of quartz, 2.5 Mt assumed to be used for silicon metal	Brown et al. (2021), USGS (2021)
Main producing countries (2020)	China 66 %, USA 8 %, Brazil 7 % Norway 6 %. Norway's share is about 50 % of the Si metal produced in Europe.	USGS (2021)
Nordic refinery and smelter production (tons of metal)	Norway 240,000 t/a; Iceland: 36,000 t/a (estimated)	Elkem (pers. com. 2021), PCC BakkiSilicon (pers. com. 2021)

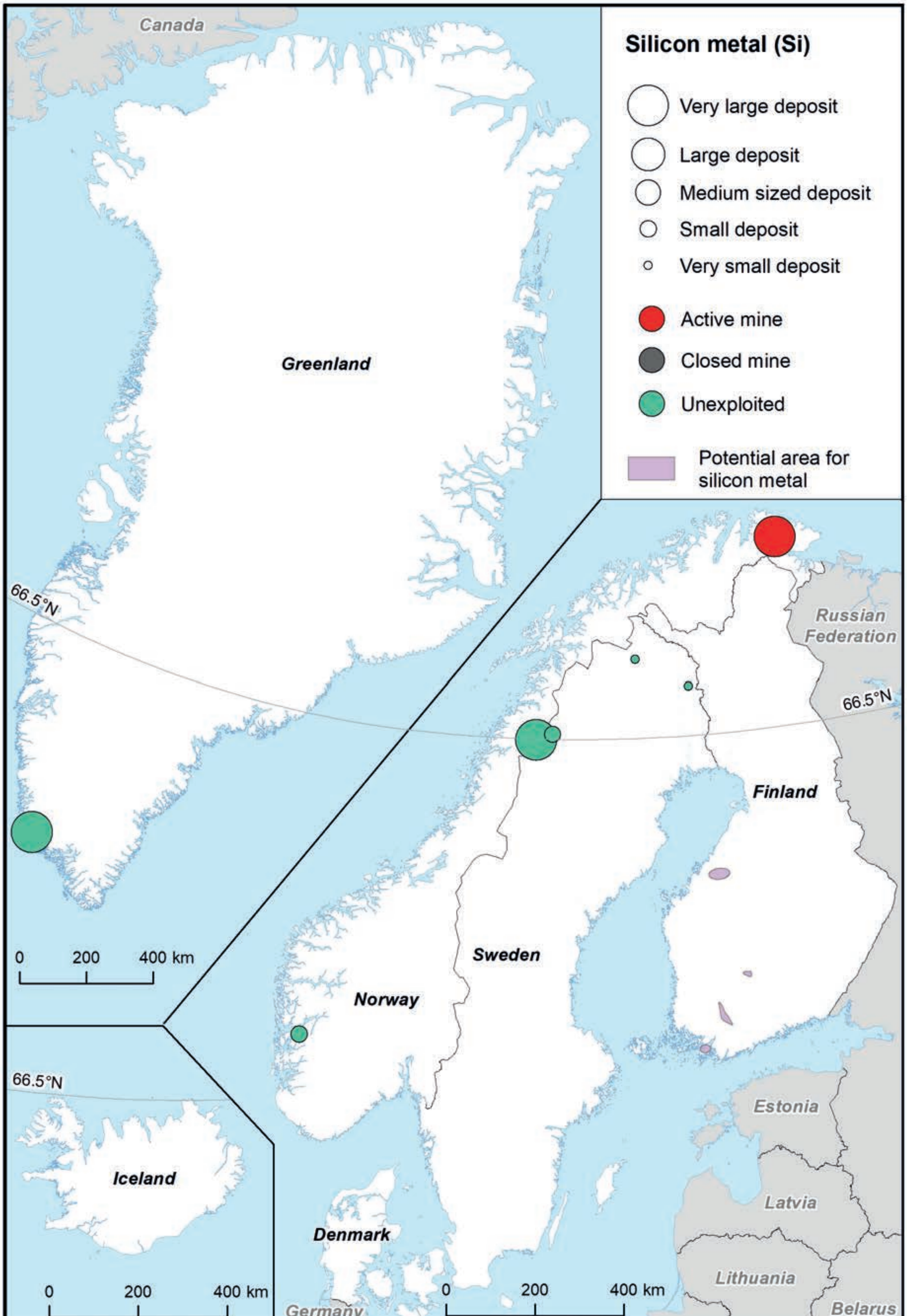

Figure 25. Locations of deposits with known silicon metal resources and areas with known or assumed potential for silicon metal resources in the Nordic countries.

3.19 Tantalum (Ta)

Commodity	Tantalum (Ta)	Data source
Uses of the commodity	Main uses: ***Capacitors***, sputtering targets, superalloys. Minor uses: Carbides, medical products, chemicals, mill products. Future uses: Computer equipment and other uses in ***electronics***, aerospace, sources of gamma radiation.	Latunussa et al. (2020)
Mine production, resources and additional resource potential in the Nordic countries	No current mine production in the Nordics. Known resources: Finland 477 t, Greenland 1,093,147 t, Sweden 68 t. Resource potential: Finland: Potential resources probably reasonably large but no assessments been done. Greenland: Resource potential is much higher than what the known resources suggest. Norway: Unknown. Sweden: Potential resources probably reasonably large but no assessments been done.	Stensgaard et al. (2016), Thrane (2016) Lauri et al. (2018), FODD (2020)
Global production (2020)	Mine production: 1,700 t Ta.	USGS (2021)
Main producing countries (2020)	DRC 39 %, Brazil 22 %, Rwanda 16 %, Nigeria 9.4 %, China 4.1 %, Ethiopia 3.5 % (note that artisanal mining dominates, and related smuggling across borders is commonplace in Africa, and from Africa to China, so country statistics are probably not correct)	USGS (2021)
Nordic refinery and smelter production	None	

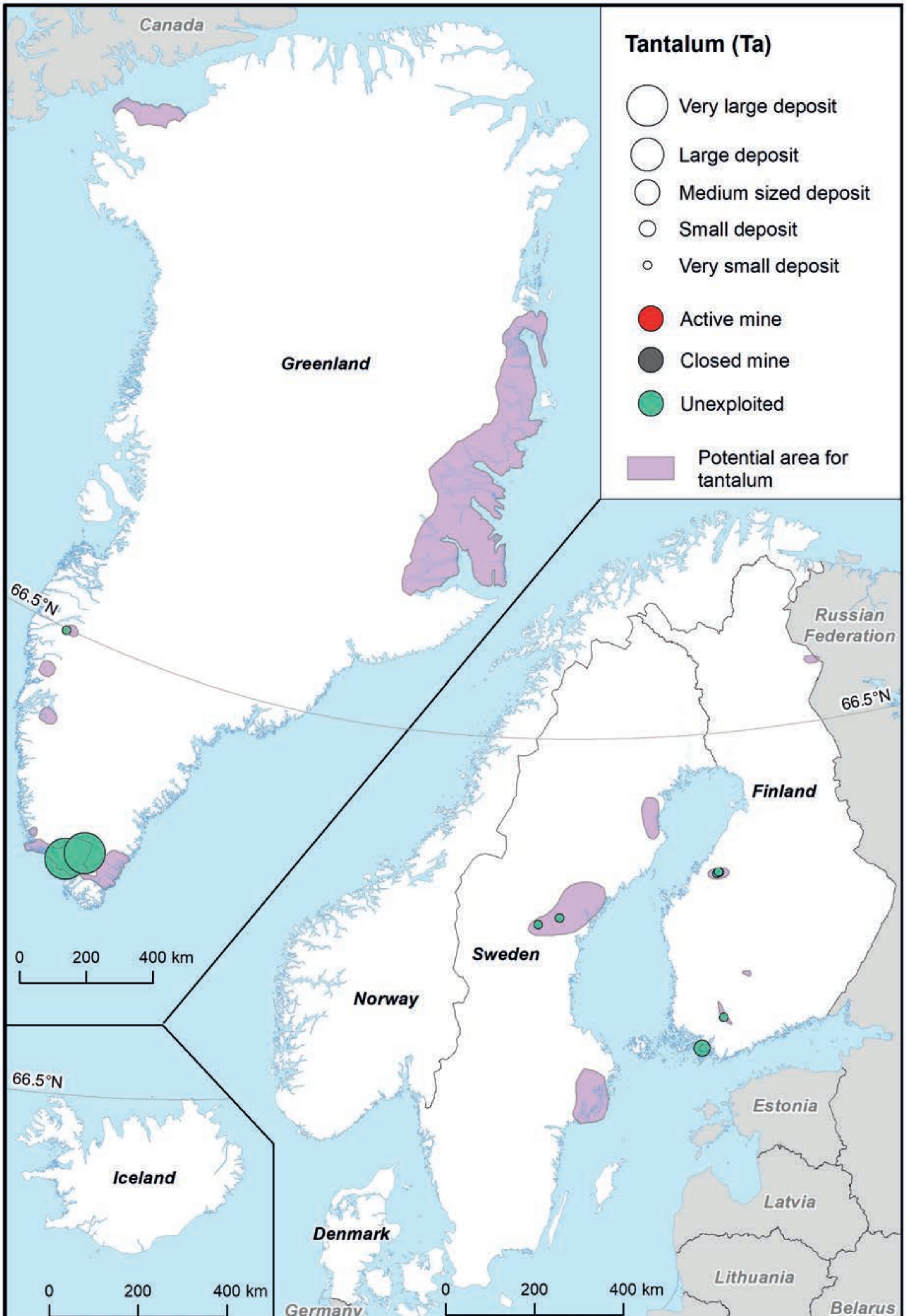

Figure 26. Locations of deposits with known tantalum resources and areas with known or assumed potential for tantalum resources in the Nordic countries.

3.20 Titanium (Ti)

The titanium-iron mineral ilmenite accounts for about 89 % of the world's consumption of titanium and the rest comes from the titanium oxides rutile and anatase. The end-user product is titanium oxide (TiO_2). Only a small fraction of mined titanium minerals worldwide ends up as titanium metal.

Commodity	Titanium (Ti)	Data source
Uses of the commodity	Main uses: Paints, polymers Minor uses: Paper, aerospace, medical equipment, ***automotive***, hardmetal, other alloy uses Future uses: Paint and polymer use to dominate, ***alloy use to increase*** (aerospace, automotive, construction)	Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production: 189,000 t Ti (all from Norway). Known resources: Finland 17.3 Mt, Greenland 57.4 Mt, Norway: 99.4 Mt, Sweden: 6.1 Mt. Resource potential: Finland: Assumed to be moderate, are under assessment. Greenland: 'Undiscovered resources' at regional scale estimated to 65 Mt Ti. Iceland: Minor potential for on- and offshore titanium deposits derived from gabbro intrusions, Lón district, Southeast Iceland. Norway: Assumed large. Sweden: Not known.	Hafstað et al. (1992), 21stNorth (2016), NGU (2016), Sørensen et al. (2016), FODD (2020), Latunussa et al. (2020), Dundas (2021)
Global production (2020)	2.4 Mt (titanium content in mined ore)	USGS (2021)
Main producing countries (2020)	Mine production: China 28 %, South Africa 13 %, Australia 12 %, Canada 8.3%, Mozambique 7.3 %, Norway 4.9 %. Titanium metal production (8–10 % of all Ti mined): China 50 %, Japan 25 %, Russia 17 %.	USGS (2021)
Nordic refinery and smelter production (tons of metal)	Norway produces 36,000 t/a TiO_2 from 100,800 t/a of ilmenite (Kronos Worldwide, Fredrikstad)	

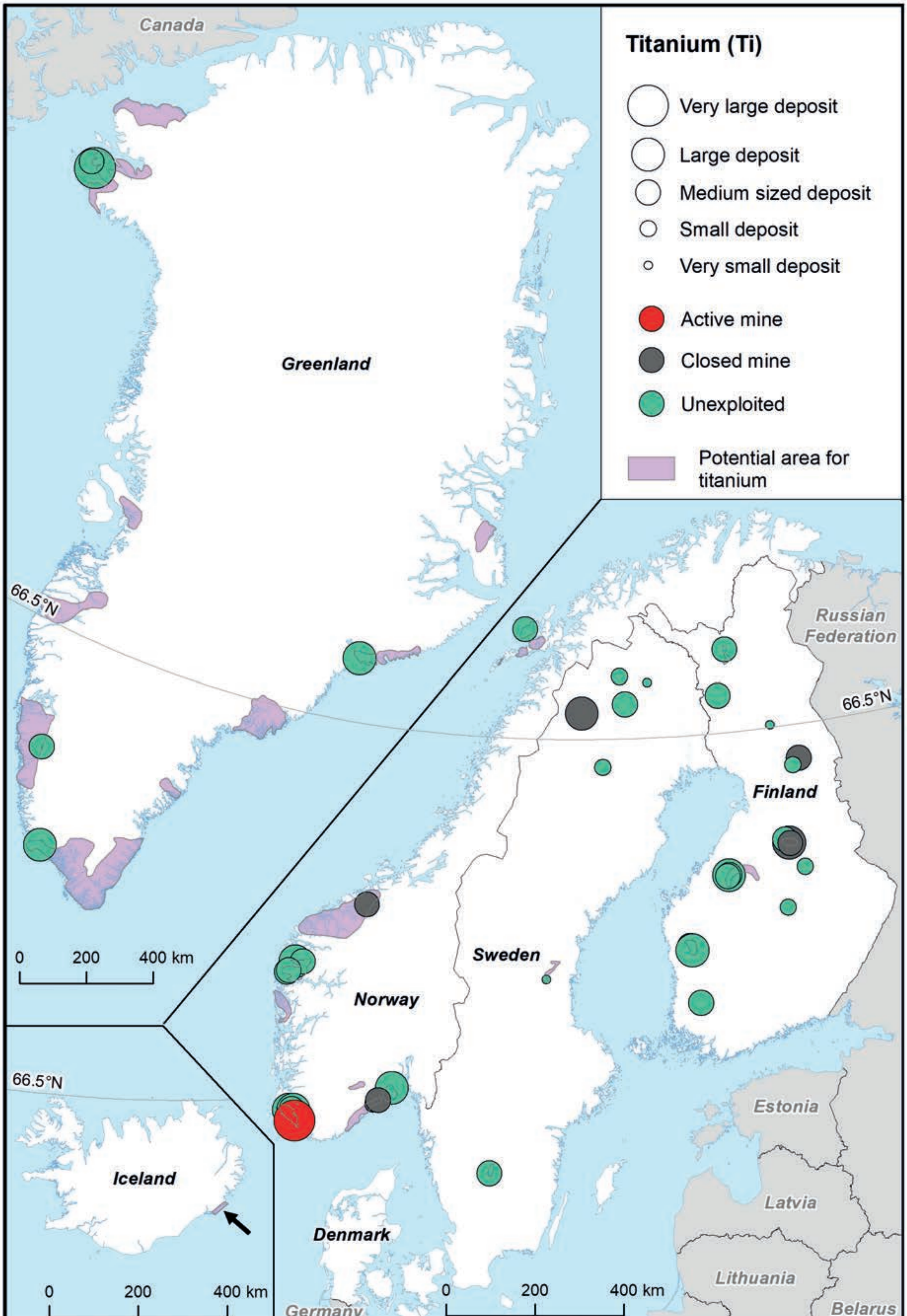

Figure 27. Locations of deposits with known titanium resources and areas with known or assumed potential for titanium resources in the Nordic countries. The associated resource-potential area in Iceland is assumed to be very small, hence indicated by a black arrow.

3.21 Tungsten (Wolfram, W)

Commodity	Tungsten (W)	Data source
Uses of the commodity	Main uses: Hard metals (tungsten carbide) 60 %, alloy steel 13 % Minor uses: Superalloys, heavy alloys, various electronic products, x-ray tubes, radiation shielding, military applic ations, catalysts Future uses: Growing uses in: automotive industry (currently 30 % share), industrial engineering, mining & construction, aviation and ***energy***	Latunussa et al. (2020), USGS (2021)
Mine production, resources and additional resource potential in the Nordic countries	No current mine production in the Nordics. Known resources: Finland 2,300 t, Norway 2,625 t, Sweden 1,770 t, Greenland 819 t Resource potential: Finland: Known resources and occurrences suggest a minor additional resource potential. Greenland: 'Undiscovered resources' at regional scale estimated to 501,000 t W; several W deposits in central East Greenland commonly associated with Sb. Norway: Known resources suggest additional resource potential. Sweden: Large remaining potential in central Swedish deposits (in Bergslagen).	Harpøth et al. (1986), Müller & Furuhaug (2008), Rosa et al. (2014), Stensgaard et al. (2016), Lauri et al. (2018), FODD (2020)
Global production (2020)	84,000 t	USGS (2021)
Main producing countries (2020)	China 82 %, Vietnam 5.1 %, Russia 2.6 %	USGS (2021)
Nordic refinery and smelter production	None	

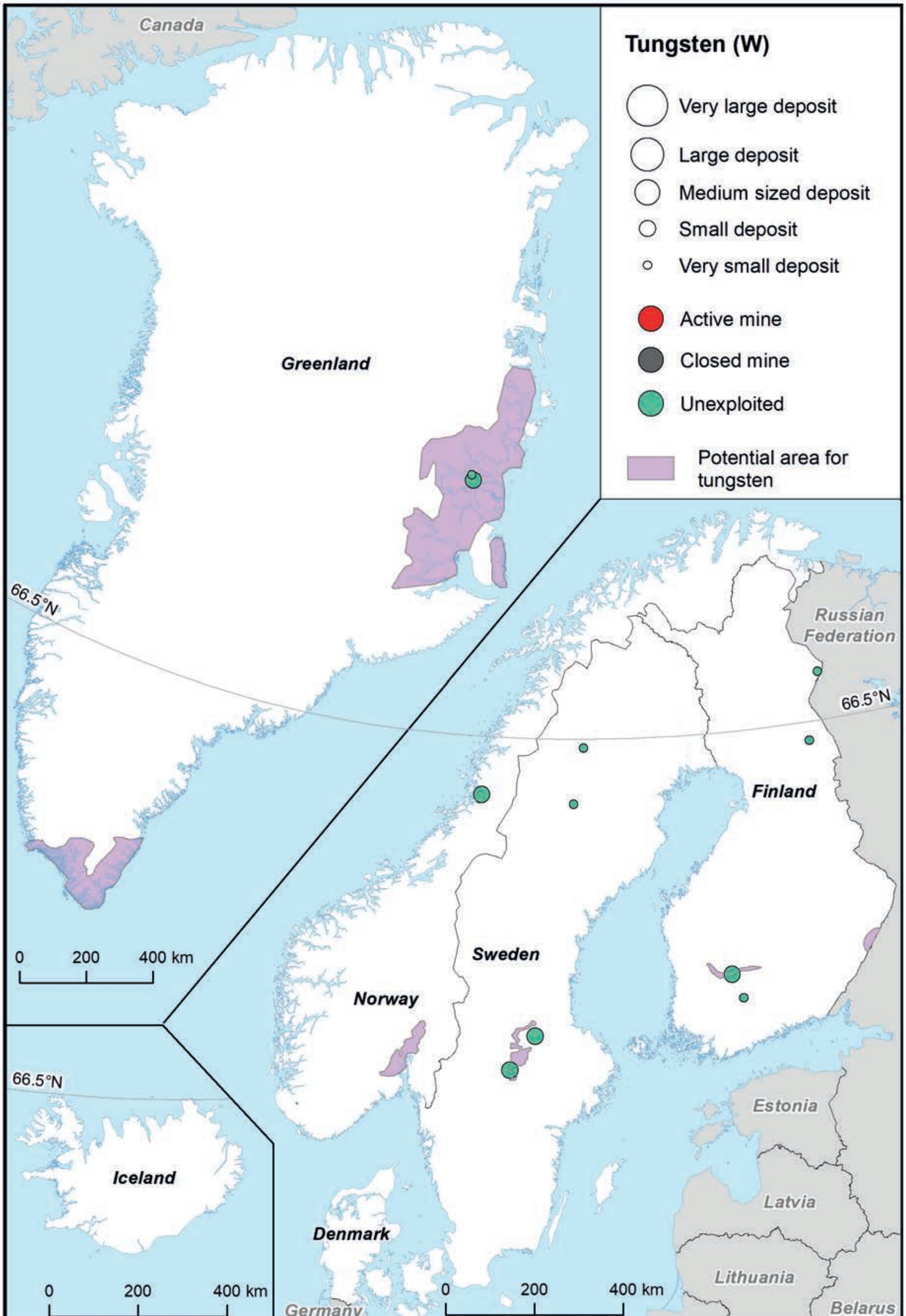

Figure 28. Locations of deposits with known tungsten resources and areas with known or assumed potential for tungsten resources in the Nordic countries.

3.22 Vanadium (V)

Commodity	Vanadium (V)	Data source
Uses of the commodity	Main uses: High-strength low-alloy (HSLA) steels, special steels (jointly 90 %) Minor uses: Super alloys, chemicals, catalyst, glass, ***redox batteries*** Future uses: Use in steel will dominate the demand in short term. ***Vanadium redox batteries*** to overtake other demands (already in rapid growth) are expected to be important for the green energy transition and drive the demand increase; ***by 2050 may demand the full volume of the current total V production.***	Bushveld Metals (2020), Hund et al. (2020), Latunussa et al. (2020), USGS (2021)
Mine production (2020), resources and additional resource potential in the Nordic countries	No production in the Nordic countries. Known resources: Finland 1,085,500 t, Greenland 1,372,700 t, Norway 318,360 t, Sweden 4,161,850 t. Resource potential: Finland: Potential resources under assessment, are probably large Greenland: Possibly large Iceland: Unknown. Norway: Unknown Sweden: Probably large but of low grade	Karinen et al. (2015), Stensgaard et al., (2016), FODD (2020)
Global production	Mining 86,000 t (2020), plus roughly 20,000 t from secondary sources (since 2018)	Bushveld Metals (2020), USGS (2021)
Main producing countries (2020)	Mine production: China 62 %, Russia 21 %, South Africa 9.5 %, Brazil 7.7 %	USGS (2021)
Nordic refinery and smelter production	None currently	

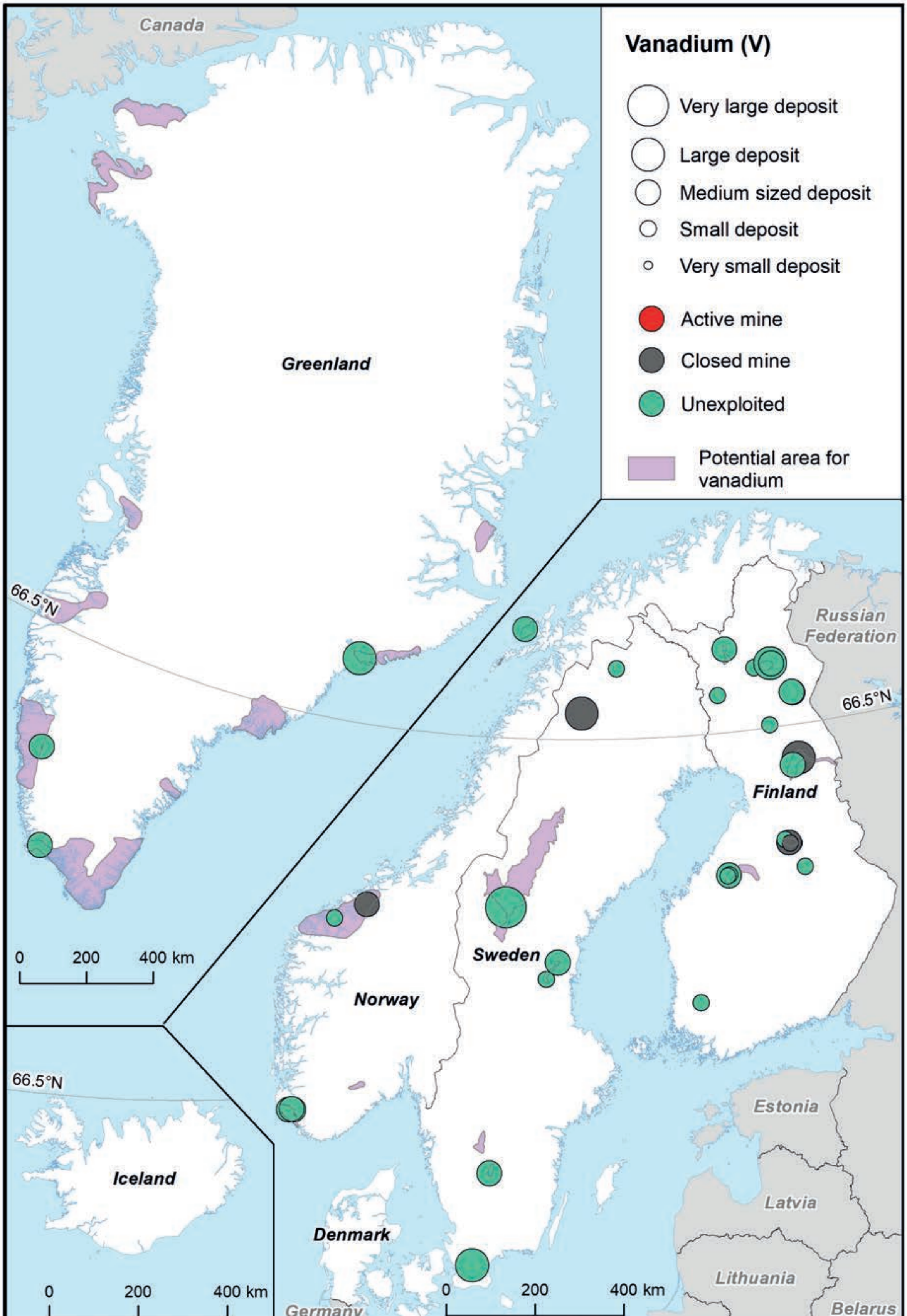

Figure 29. Locations of deposits with known vanadium resources and areas with known or assumed potential for vanadium resources in the Nordic countries.

3.23 Non-critical and future raw materials that are, or may become, essential for the green energy transition

3.23.1 Copper, manganese, nickel

Several non-critical raw materials are needed in the construction of wind turbines and solar panels, such as aluminium, boron, chromium, copper, iron, lead, manganese, molybdenum, nickel and zinc (Carrara et al. 2020). Other, at the present, non-critical elements, like cadmium, chromium, silver and tellurium are essential for the energy solutions (e.g., batteries), see Hund et al. (2020).

In this subsection, we give information on three of these, copper, manganese, and nickel. These three metals are in several ways essential in building carbon-free energy systems: They are needed in the necessary infrastructure (Cu: cables, wiring, heat exchangers, electric motors, solar panels; Mn and Ni: steels and other alloys) and in batteries. While much of copper is used as refined metal, most of manganese and nickel are refined and smelted directly into alloys with iron. Another issue with copper and nickel, especially, is that their use in energy solutions is expected to increase to seriously compete with their other uses.

Aitik mine, Sweden. Photo E. Jonsson.

Commodity	Copper (Cu)	Data source
Uses of the commodity	Main uses: ***Power cables and wiring***; building (pipes, taps, valves, fittings, roof plates) Minor uses: Automobile parts; electric motors; ***heat exchangers and radiators***; pressure vessels and vats; superconductors; ***CIGS solar cells*** Major future uses: ***Cables and wiring; electric motors; other uses in electric vehicles; various IT/digital applications; photovoltaic (CIGS and wiring)***; building and infrastructure	Eynard et al. (2020), ICSG (2020)
Mine production (2020), resources and additional resource potential in the Nordic countries	Mine production 135,610 t (Finland and Sweden). Known resources: Finland 4,820,000 t, Greenland 72,730 t, Norway 1,882,000 t, Sweden 11,768,000 t. These are minimum estimates, as Cu grades are not known or are only partially known for many PGM and zinc deposits which contain potential byproduct Cu. Resource potential: Finland: 'Undiscovered resources' at regional scale estimated to 9,669,000 t Cu. Greenland: 'Undiscovered resources' at regional scale estimated to 3,345,000 t Cu – this only covers the sedimentary copper deposit type. Iceland: Small potential for copper in Lón district, Southeast Iceland. Norway: Distinct additional potential in areas with closed mines or known resources. Sweden: 'Undiscovered resources' at regional scale in the Skellefte district estimated to 726,000 t and in the Caledonides 145,000 t Cu, whereas other regions still lack such assessment.	Fleming et al. (2006), Carranza and Sadeghi (2010), Stensgaard et al. (2011), Rasilainen et al. (2017), Bjerkgård et al. (2020), FODD (2020)
Global production (2020)	20,600,000 t Cu (mine production); 24,400,000 t Cu (refinery production)	ICSG (2021)
Main producing countries (2020)	Mine production (in 2020, USGS data): Chile 29 %, Peru 11 %, China 8.5 %, Democratic Republic of Congo (DRC) 6.5 %, USA 6.0 % Refinery production (in 2020, USGS data): China 39 %, Chile 9.6 %, Japan 6.4 %, DRC 4.4 %, Russia 4.3 %	USGS (2021)
Nordic refinery and smelter production (tons of metal)	Finland: 148,438 t; Norway: 21 962 t; Sweden: 266,000 t	National statistics for 2020

Commodity	Manganese (Mn)	Data source
Uses of the commodity	Main uses: Steel (about 90 %) Minor uses: Aluminium-manganese and copper-manganese alloys, ***dry-cell and lithium batteries***, pigments, catalysts Major future uses: Steel; ***battery use increasing rapidly but remaining minor relative to Mn demand in steel***	Eynard et al. (2020)
Mine production (2020), resources and additional resource potential in the Nordic countries	No current mine production. Known resources: Finland 4,753,000 t, Sweden 5,943,700 t. Resource potential: Finland: Major potential is in the Talvivaara-type Ni-Zn ores. Greenland: No records of Mn occurrences Iceland: Unknown. Norway: Only insignificant Mn occurrences are known from Norway. Sweden: Main potential is in iron deposits.	FODD (2020)
Global production (2019, 2020)	18,500,000 t in manganese content of mined ore (2020). Total smelter production not known.	Brown et al. (2021), USGS (2021)
Main producing countries (2020)	Mine production (2020): South Africa 28 %, Australia 18 %, Gabon 15 %, Ghana 7.6 %, China 7.0 %, Brazil 6.5 %.	USGS (2021)
Nordic refinery and smelter production	Norway: 270,000 t ferro-manganese, 230,000 t silico-manganese	ERAMET, pers. comm.

Commodity	Nickel (Ni)	Data source
Uses of the commodity	Main uses: ***Stainless steels*** (>65 %) Minor uses: Superalloys, non-ferrous alloys, ***batteries***, coatings, catalysts, foundry products Major future uses: ***Stainless steels (essential in many energy applications); battery demand assumed to overtake steel***, alloys	Eynard et al. (2020)
Mine production (2020), resources and additional resource potential in the Nordic countries	Current mine production 41,429 t (Finland) Known resources: Finland 4,960,000 t, Norway 108,000 t, Sweden 2,568,000 t – these are minimum estimates, as Ni grades are not known or are only partially known for many shale, PGE and talc deposits which contain potential byproduct Ni. Resource potential: Finland: 'Undiscovered resources' at regional scale estimated to 5.9 Mt Ni. Additional major potential in Talvivaara-type Ni-Zn deposits. Greenland: Several promising exploration projects for Ni are active but no resource estimates from these projects are available. 'Undiscovered resources' at regional scale estimated to 3.8 Mt Ni. Iceland: Unknown. Norway: Additional potential in magmatic deposits. Sweden: Extensive potential, particularly in shale-hosted deposits.	Rosa et al. (2013), Rasilainen et al. (2017)
Global production (2020)	2,431,500 t Ni (mine production, roughly equals to refinery and smelter production)	USGS (2021)
Main producing countries (2019, 2020)	Mine production (2020, USGS data): Indonesia 30 %, Philippines 13 %, Russia 11 %, New Caledonia 8.0 %, Australia 6.8 %, Canada 6.0 % Refinery and smelter production (2019, BGS data): China 32 %, Indonesia 16 %, Russia 9.1 %, Japan 7.3 %, Canada 5.0 %	Brown et al. (2021), USGS (2021)
Nordic refinery and smelter production (tons of metal)	Finland: 90,837 t; Norway: 92,132 t (from imported matte)	National statistics for 2020

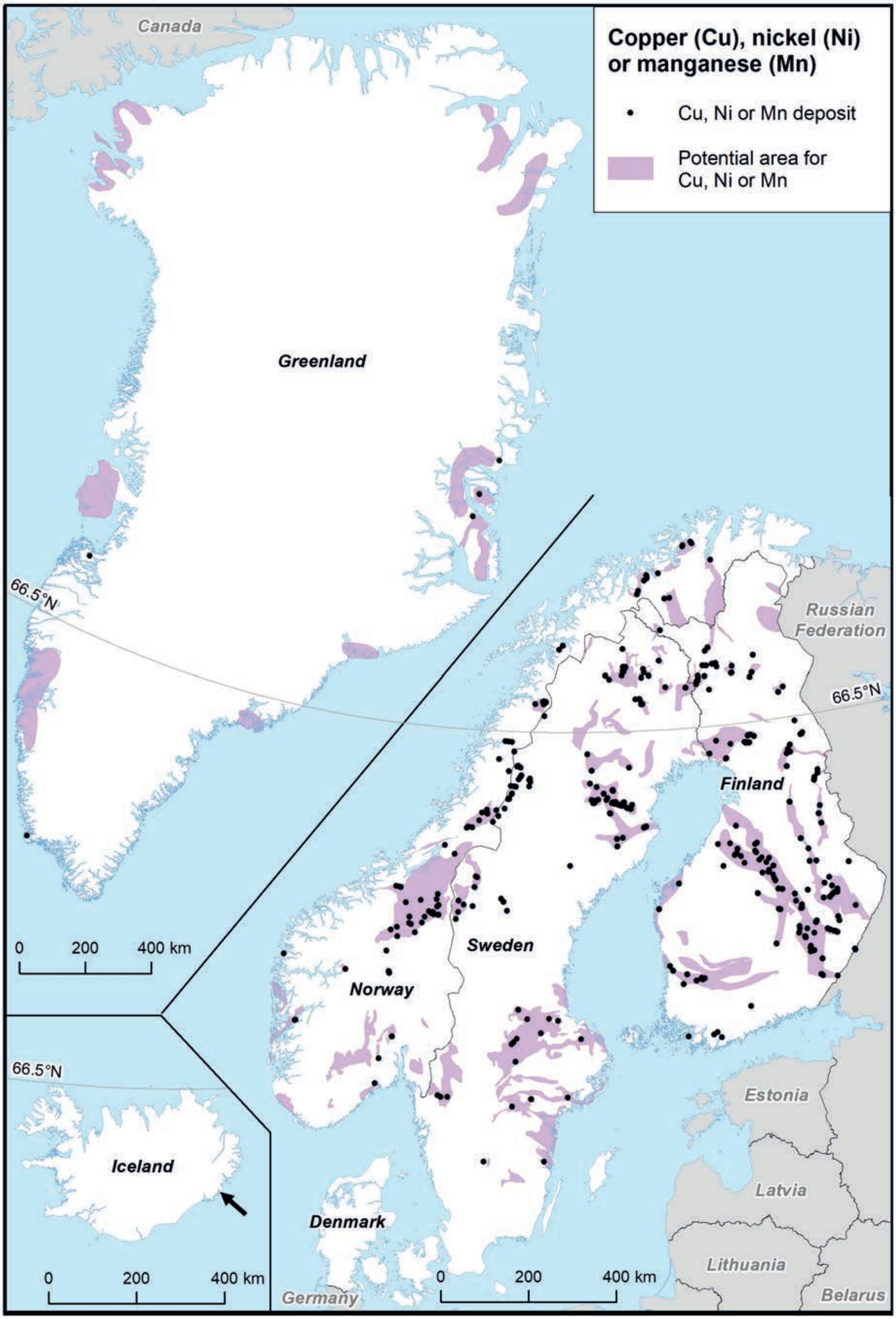

Figure 30. Locations of deposits with known copper, manganese and/or nickel resources and areas with known or assumed potential for additional resources of these metals in the Nordic countries. The associated resource-potential area in Iceland is assumed to be very small, hence indicated by a black arrow.

3.23.2 Basalt fibers

Basaltic rock is the dominant rock type in Iceland. To create basalt fiber, the basalt rock is mined and finely crushed and blended to achieve the desired composition. Finally, the material is heated in furnace to an optimal temperature of between 1400–1600°C. The molten basalt is extruded into continuous filaments with a diameter of 8–14 μm. Continuous Basalt Fibre (CBF) may be formed into, e.g., chopped strands or woven fabrics (Johannesson et al. 2016). Further processing can be achieved by in combing CBF and resin to produce reinforcement materials for specific applications such as body parts for cars, windmill blades, boats and reinforcing bars for concrete structures (Thorhallsson & Snaebjornsson 2016).

The Greenbas project (2014–2016), financed by NordMin, investigated the sustainable production of CBF from basalt mining and documented a signi ficantly reduced carbon footprint specially by using green energy in the basalt melting process from Hydro and Geothermal power plants (Johannesson et al. 2016). The project identified possible mining sites (Figure 31), and prepared the next stage for a small-scale, all-electric pilot testing to further develop production of Basalt Fiber Reinforced Polymer (BFRP) in Iceland.

The production of BFRP composites offers a sustainable alternative to the traditional energy-intensive reinforced steel within building and construction industry and, hence, be one piece in the way towards low-carbon society and green energy transition (Inman et al. 2017).

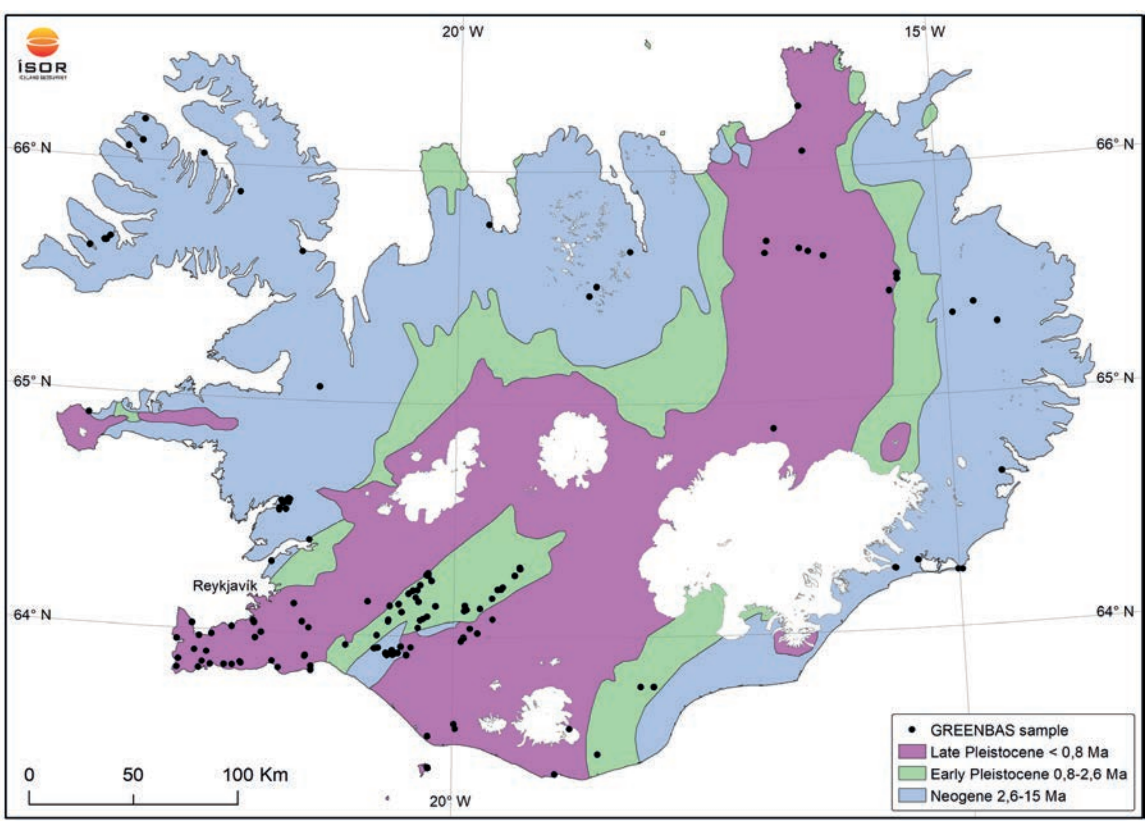

Figure 31. Basalt fibre raw material sampling sites in Iceland (modified from Johannesson et al. 2016). Ma = million years (age of rocks).

View from drill site, Storø project, Greenland. Photo H.Stendal.

4 Discussion and Conclusions

As has been shown in the fact sheets, tables, text and maps of this report, the Nordic countries do have a significant, albeit variable, potential with regards to a future supply of critical metals and minerals. Many of them, such as cobalt, lithium and the rare earth elements are vital for the technologies that are at the core of achieving a green energy transition for both industry and society at large. It is very important to stress that for the absolute majority of CRMs there are no indications that the demand from other industrial sectors is decreasing. As described early on in this report, recycling is not an option to meet all or even a major part of the rapidly increasing demand scenarios for most CRMs, which a green energy transition will necessarily generate. Moreover, possible substitutes for these CRMs either do not exist (e.g., for the REE and the PGE), or if they actually do and are used, lead to significant decreases in the performance of typical applications and, consequently, to ineffective and wasteful use of both mineral and energy resources (e.g., Latunussa et al. 2020). Furthermore, a suitable substitute is typically available from similar or the same ores as the one to be substituted, hence featuring the same problems in finding the deposits, and in extraction and recovery as the one to be substituted (Graedel & Nassar 2013). Thus, developing new (Nordic) CRM deposits towards the extraction stage will become essential.

Jointly, the Nordic countries have a bedrock similar to the major mineral-rich countries across the globe, such as Canada, USA, Australia, South Africa, and Brazil (Eilu 2012, Boyd et al. 2016). The large land area combined with a long and, especially, diverse geological history explains the extensive mineral resources and the still untapped CRM potential of the Nordic countries as a whole (Figure 32). Between the Nordic countries, there also are major differences in their geology. This has an overarching control on the potential for many types of mineral deposits, with each deposit and country thus having a specific potential for individual CRMs, as is seen in Section 3, above. Logically, this is also the case for those raw materials directly relevant for green energy transition technologies. Finland, Norway and Sweden also have a long history in mining, processing of the ores and developing mining and metallurgy technology. Immediately below, we summarise for each country their CRM endowment and their most significant CRM refinery industry, not forgetting the currently non-critical metals also needed in the future low-carbon energy solution.

The information presented above and summarised below is the result of searching and collating information separately from national geoscientific and mineral databases. This and similar work would be vastly improved if there was a joint-Nordic deposit and mineral-potential belt database. The European Minerals4EU database (http://www.minerals4eu.eu/) is available, but does not have much data coverage and has inherent issues, including not being up to date. Another and better source for deposit data in this region is the Fennoscandian Ore Deposit Database (https://www.gtk.fi/en/fennoscandian-mineral-deposits-application-ore-deposits-database-and-maps/), which, however, does not cover Denmark, Iceland and Greenland, and lacks commodity information, unless that particular commodity has been characterised as part of a reported mineral resource. The latter issue is very typical for the CRMs. In addition, there is no database on secondary mineral resources in the Nordics – these should be included in the same database as the primary resources, because much of the relevant secondary resources are directly associated with existing mine sites. The lack of quality data on secondary deposits in Europe has been highlighted, including in recent EU projects (e.g., the SCRREEN project; Ladenberger et al. 2018). Consequently, a Pan-Nordic database with full details and information on CRM and other metal and mineral resources and their potential in primary as well as in secondary deposits would become extremely useful, not only for research and mineral exploration but also for mineral policies, land use issues, and other decision making.

Finland

Currently, Finland is the only country in Europe with primary (mine) production of cobalt, phosphate, and platinum group metals. Finland also hosts significant cobalt, copper, manganese, nickel, and PGM resources and potential for future production. In addition, Finland has identified resources for lithium, graphite, phosphorus, vanadium, titanium, and potential for beryllium, niobium, REE, scandium, tantalum and tungsten. Additional, major 'undiscovered' cobalt, copper, nickel, PGM, phosphate, REE, titanium, and vanadium resources are statistically estimated for Finland (Rasilainen et al. 2017, 2020). The ultimate explanation to this extensive mineral endowment is that, as Greenland, the geology of Finland is most similar of the Nordic countries to the mineral-rich parts of Canada, Australia, and South Africa.

Like Sweden and Norway, Finland has a major metal refinery and smelter industry providing raw materials for the global manufacturing industry. Of mention are, that 10 % of all cobalt in the world is refined in Finland, the Europe's largest nickel and cobalt battery chemical production plant at the Terrafame mine has just started production, and the first mine (Keliber) to produce battery-grade lithium in Europe is under construction in western Finland. A major untapped CRM resource is the Sokli phosphorus deposit which may contain globally significant niobium, tantalum and REE resources.

Greenland

Greenland has the entire geological history of the Earth represented, ranging from the oldest to the youngest rocks on Earth. Thus, Greenland hosts a wide range of geological environments and related mineralizing processes including many of the critical raw materials used in diverse green technologies. The greatest CRM exploration targets are among metals such as the rare earth elements (REE), niobium, tantalum, titanium, hafnium, platinum group metals (PGM), phosphorus and vanadium, as well as industrial minerals such as fluorspar. Another interesting indicator of the good CRM potential of Greenland is shown by the map in Figure 32 depicting nearly all of the ice-free part being potential for the CRMs.

In Greenland, the Kringlerne Zr-REE deposit already has a mining license and might come into production in the near future. The proportion between LREE and HREE is 69 % LREE and 31 % HREE. In the latter Y yields 19 % (Tanbreez 2021). In addition, the deposit has a geological resource of 6 Mt Nb and 1,100,000 t Hf. Some other Nb deposits in Greenland might have problems to be exploited due to contents of radioactive minerals.

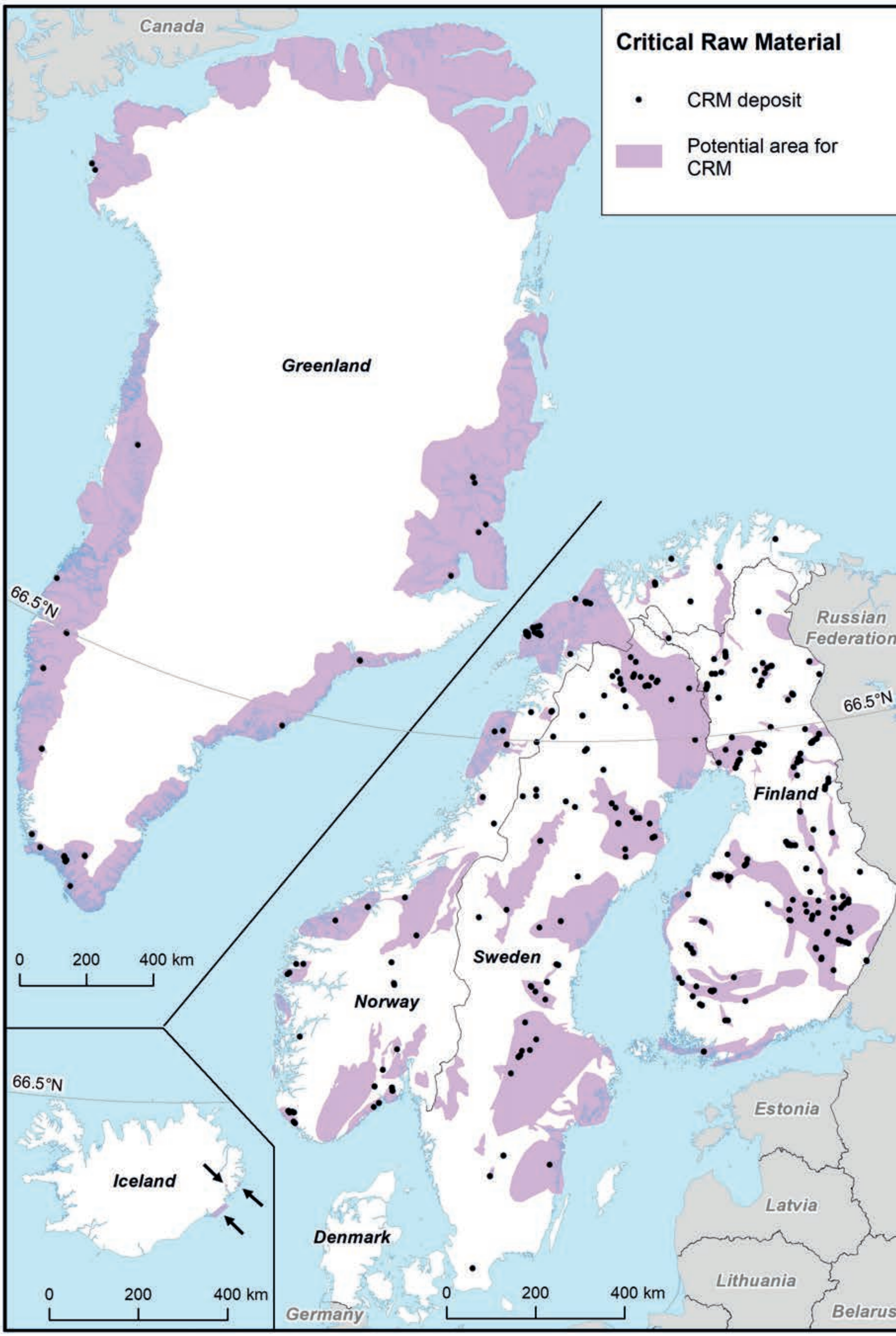

Figure 32. Locations of deposits with known critical raw material resources and areas with known or assumed potential for additional CRM resources in the Nordic countries.

Iceland

Iceland represents geologically the least diverse and youngest rocks among the Nordic countries, as it resides on top of a mantle plume within young oceanic crust. Basalt is the dominant rock type and metalliferous deposits are mainly associated with the rich and widely distributed geothermal/epithermal activity and which also provides abundant green energy through its geothermal systems. Overall, only sparse occurrences of CRMs are known, but do include baryte, fluorspar and titanium, and also minor non-CRM albeit green energy-relevant copper mineralisation.

While basaltic fibre is not a designated CRM, we include it here because of its special properties. Its production using green energy replaces the traditional energy-intensive steel production and reduces the carbon footprint. Mining of basalt would be the first of its kind in the Nordic countries for this purpose, as well as the production of Continuous Basalt Fibre (CBF) and Basalt Fibre Reinforced Polymer (BFRP). The focus is on minimising the environmental impact in all aspects of BFRP from production to application and disposal. Previous projects have prepared for the next stage of a small-scale, all-electric pilot testing to further develop a production of BFRP rebar, which combines CBF and resin to produce reinforcement materials for specific applications.

Norway

Norway has a very varied geology and compared to the rest of Fennoscandia, most of the rocks in Norway are considerably younger, which imply that the geological setting is quite different for many of the Norwegian occurrences. Norway is the most important producer of natural graphite and titanium minerals within the EU35. The largest potential for graphite in Fennoscandia is in Norway and more than 25 occurrences are identified. Norway is also a world class producer of titanium minerals that are refined to titanium oxide. Several very large titanium deposits are identified in southern Norway. The Fen area near Skien is identified as a world class potential resource for REE. In addition to its geological resources, Norway has access to cheap electric energy (in general the most expensive component of metal production). This has resulted in that Norway, for instance, is an important producer of silicon metal, nickel, and cobalt extracted from imported raw materials. With the energy transition from hydrocarbons to green energy solutions, the access to cheap electricity will by all probability be increasingly important in the future.

Sweden

Sweden has a diverse geology, which is reflected in its multitude of known mineral deposits and many centuries of past mining. Yet, despite being one of the major mining countries in Europe today - encompassing major production of copper, gold, iron, lead, tellurium, silver and zinc - there is no current production of CRMs. However, there are advanced projects and a possible near mine-restart with regards to graphite production, two advanced REE projects, as well as potentially near-future by-product extraction of phosphorus and REEs. Additionally, there are variably advanced or well-characterised projects, deposits and occurrences of e.g., fluorspar, lithium, phosphorus, tantalum, tungsten and vanadium. With regards to CRMs of by-product metal nature (e.g., antimony, bismuth, cobalt, gallium, germanium, indium), there are still large knowledge gaps with regards to both their occurrence and geological processes of formation. There are also additional recognised mineralisation types of, e.g., REE, for which the present state of knowledge is relatively low.

Also similar to Norway and Finland, Sweden has an important smelter industry, although it is presently not geared towards CRMs, it nevertheless refines metals that are vital to a green energy transition. Copper, gold, silver and lead are produced from both domestic and imported concentrates at Boliden´s Rönnskär smelter which is also a world leader in electronics recycling. Sweden also has smelter production of aluminium, both from primary and secondary sources, as well as very significant steel and iron production.

The Nordic countries – CRM potential and knowledge gaps

Based on the descriptions above, it is crucial to follow up and improve our understanding of the full resource and supply potential of Nordic CRMs and additional specific raw materials, with particular focus on those essential to the green energy transition. For practically any commodity described in this report, there is moderate to major resource potential, even if rather small known resources exist or no resource tonnages have been estimated at all, for any of the Nordic countries. In this context, it is important to note that the large number of small deposits and occurrences (compare the maps in Section 3 and Figure 32) practically always indicates a larger potential for a mineral commodity. Also important is to take into account that "all that is in the known resources and reserves is just a fraction of all the mineral commodities that there is in the ground to be extracted" (Meinert et al. 2016). As for near-future exploration, Greenland is still what we call a 'Greenfield' region (i.e., much less explored for minerals) compared to Finland, Norway and Sweden which can be categorized loosely together as a 'Brownfield' region. Denmark and Iceland, however, are exceptions as their raw material diversity is much smaller for geological reasons.


Geophysical mapping of graphite, Norway. Photo NGU.

Some Nordic CRM resources stand out in a European and even in a global context (Table 3), such as the giant REE(-Nb-Hf) reserves in Greenland, which are of absolute world-class in size; yet their location and associated logistic and other issues provide numerous challenges and therefore they do not guarantee a successful business case for new mining activities (e.g., Kalvig & Lucht 2021). In comparison, the relatively small REE(-Zr-Hf) project at Norra Kärr in Sweden, makes up significantly by its location near existing infrastructure, potential work force, etc. However, also in this case, development into an intra-European source of REE would still require access to a European facility for the refining of the REEs, in order to secure a truly European supply chain.

Table 3. Most important CRMs from the Nordic perspective. These are the ones with the largest resource and resource potential for a commodity, or have other major significance within Europe.

Commodity	Main application in green technologies (including major future uses)	Comments, reasoning
Cobalt	Essential for many electrode types in Li-ion batteries	Mine production Finland (the only Co mine production in Europe), refinery production in Norway and Finland; many deposits in Fennoscandia; additional assumed resources in Fennoscandia and Greenland.
Graphite	Essential for electrodes in Li-ion batteries	High-quality deposits, potentially large deposits in large parts of the Nordic region; active mining in Norway.
Hafnium	Solar cells (CIGS), IR and fibre optics	Very large deposit in Greenland and high potential in many zirconium-rich deposits in Fennoscandia and Greenland.
Lithium	Li-ion batteries	Moderate potential in the Nordic countries; one mine project under construction; no battery-grade Li production yet elsewhere in Europe.
Niobium	Superalloys in power generators, turbines, super-conducting magnets	Huge resources particularly in Greenland and a large potential for additional resources in Finland and Norway (8 % of globally known resources).
Platinum group metals	Essential in fuel cell and hydrogen power technology, several electronics applications	Large potential in Greenland and Finland including several very significant deposits. Within Europe mine production only in Finland. Additional potential from Ni and talc deposits as byproducts.
Rare earth elements	Magnets for electric motors and generators in vehicles and wind turbines, also fuel cells and batteries	Large resource potential identified, including world class deposits in Greenland, Sweden and Norway (9 % of globally known resources), major assumed additional potential in Finland.
Silicon metal	Solar photovoltaic applications, semiconductors, silicon anodes in future Li-ion batteries	Production in Norway and refining in both Norway and Iceland; large resources of high-purity quartz in Norway and major potential in large parts of the Nordics.
Tantalum	Capacitors and other electronics	Large resources are identified in Greenland, significant additional resources are expected in Greenland and probably also in Finland and Sweden.
Titanium	Light-weight alloys for vehicles and electricity-related structures of all kinds	Significant production in Norway and large resources identified in Norway, Greenland, Finland (25 % of globally known resources).
Vanadium	Stationary redox batteries	10 % of the globally know resources are in the Nordic countries, particularly in Sweden.

While Finland has the only significant current production of cobalt in Europe, additional mineral occurrences and past producing mines are known from Norway and Sweden. As for vanadium, which is likely to become a key metal in near-future green energy storage systems, Finland, Greenland, Sweden and partly also Norway have large known resources. With regards to, e.g., graphite and titanium, Norwegian resources and production are already very significant on a European scale, while Swedish production may start again; lithium deposits with future potential are known from Finland and Sweden, whereas niobium and tantalum are found in variable abundances in both Greenland and Fennoscandia, to mention a few selected cases. Yet, in most of these mineralised regions, focused research on the specific critical metals and minerals and their links to geological evolution and particular processes is lagging behind very significantly in comparison to that relevant for the traditionally mined metals, and in the case(s) of the by-product CRMs, the state of knowledge is actually quite poor in most of the Nordic countries.

In addition to the factual and inferred resource potential of Nordic CRMs, there is an urgent need to ensure higher environmental, social and governance standards for exploitation and production of CRMs on a global scale. The Nordic countries have an advantage here due to a combination of a long-standing and high-tech mining industry combined with strict environmental and health regulations of mining and mineral processing compared to many other mining regions worldwide. Expanding mineral production in the Nordic countries would both make the region more resilient to supply risk, but also help to secure a more responsible sourcing of the raw materials that are essential and critical for a green energy transition within our countries. This should also include the development of CRM-related refining and manufacturing capacity in the Nordic countries, providing jobs and economic growth, besides the obvious safeguarding of a local and regional chain of production.

The follow-up work should take the form of a full-scale project or, more probably, several inter-linked projects as outlined below, focused on bridging these gaps in our present knowledge of the future supply potential of such metals and minerals in the Nordic countries. One of the information gaps are mineral resources on the Nordic sea floor, especially in the Reykjanes, Kolbeinsey, Jan Mayen and Iceland-Faroe ridges, the oceanic shelf around Iceland and Greenland, as well as the Baltic sea.

A proposed full-scale Nordic mineral deposit database would also help in indicating and filling gaps in the current knowledge of both primary and secondary resources. In this overall context, it is also vital to look into and characterise the *entire* metal and mineral demand and potential supply situation for the green energy technologies, as several of them are presently not classified as critical by the EU assessment. Notably, what is not critical today may very well be critical within a year or two (e.g., Blengini et al. 2017, 2020). Furthermore, the links between present and future production of major (base and precious) metals and that of potential future by-product critical metals (cf., the issue of metal companionality, Section 2.2) must be thoroughly worked out. This would, among other things, involve extensive sampling and analysis of material from both old and recent mining districts and other prospective regions with poorly known minor metal contents as well as updating of relevant deposit type classifications.

Additionally, Finland, Sweden and Norway have a very long history of mining and refining of a variety of ore deposits and ore types, resulting in extensive remnant and current wastes at the mine sites, as well as near smelters and refineries. Additional secondary resources could potentially be provided by the urban environment. The possibilities of urban wastes to cover any significant amount of CRM demand look meagre, however, as the existing information suggest very low metal concentration levels and, consequently, recovery will be both expensive and energy-intensive (e.g., Prabhakar et al. 2021).

The full future potential of recycling and extracting CRMs from both primary and secondary sources should also be investigated on a broad scale, to take the entire material flow in the life cycle of the raw materials into account, to explore where recycling, additional to that already taking place, can be applied as part of the supply chain. Such an assessment needs to take into account also the energy input needed for CRM recovery from the secondary sources. Also important is to note here that a lot of possible 'waste' materials already are fed back into the processing at mines, refineries, smelters and in manufacturing. More significantly, if the right kinds of incentives are introduced, the recovery of such minor metals that are currently not, or only sparsely extracted during processing, could be vastly improved. A prime example of the latter is the metal germanium (Ge), for which it is estimated that, globally, only about 3 % of the Ge contained in zinc concentrates (the main Ge source) is currently recovered at refineries (USGS 2021).

REE host mineral eudialyte in outcrop at Norra Kärr, southern Sweden. Photo E. Jonsson.

5 Recommendations

Above, we have shown that there is plenty of relevant information for the Nordic countries, but also major gaps in essential data and information. Hence, we recommend the following work to be done as immediate actions. Cooperation beyond the organisations who produced this report is likely to be needed for these topics. Most probably, the recommendations can be implemented in the form of 3 to 4 full-scale projects:

1. **Research on how to expand or initiate CRM exploration, sustainable domestic production and processing capacity from *primary sources*.** This is the core of all work to be done, and includes both metals that currently are extracted and those that are mostly not or not at all recovered from the mined ores.
   - In order to contribute to meet raw materials needs, the Nordic mineral resource potential should be thoroughly investigated. With a few exceptions (such as Co, PGMs, Ti and V), the knowledge base is poor for most of the critical raw materials.
   - Assess poorly known but high-potential mineral deposit types in geologically favourable areas and identify which data can be generated by government institutions to provide the foundation for or accelerate private industry investments.
   - Produce maps indicating potential areas and compile relevant geoscience and industry data in easily accessible data packages, that in turn are readily updated as new data and other information become available.
   - The Nordic sea floor resource potential should be assessed in the CRM context.
   - Investigate energy-efficient mineral processing and CRM-based component production technology.

2. **Research on CRM amounts and distribution, and how to expand or initiate sustainable domestic production and processing capacity from *secondary sources,*** including mine, refinery and smelter side streams and waste, and recycling of end-of-life products (a circular economy approach).

3. **Create a *Nordic database* on primary and secondary resources.** This database would be created by using both existing and, in particular linked to point 1 above, new data on known deposits.

4. **Investigate and characterize *the entire metal and mineral demand***, and the potential supply situation for the green energy technologies, as several of these commodities are presently not indicated as critical. This work should include *forecasts* on the future material flow for short, medium and long term.

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Appendix 1. Abbreviations used and chemical elements mentioned in this report

Al	Aluminium (Aluminum)
Ba	Barium
Be	Beryllium
BFRP	Basalt Fiber Reinforced Polymer
BGS	British Geological Survey
Bi	Bismuth
CBF	Continuous Basalt Fibre
CIGS	Copper-indium-gallium-selenide solar cell (or CIGS cell, sometimes CI(G)S or CIS cell) is a thin-film solar cell (PV cell) used to convert sunlight into electric power
Co	Cobalt
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CRM	Critical raw material
Cu	Copper
EC	European Commission
EI	Economic Importance
EU	European Union
Ga	Gallium
Ge	Germanium
GEUS	Geological Survey of Denmark and Greenland
GTK	Geological Survey of Finland
Hf	Hafnium
HHI	Herfindahl-Hirschman Index
HREE	Heavy rare earth elements, europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), yttrium (Y)
ICT	Information and communications technology
In	Indium
Ir	Iridium
Li	Lithium
LREE	Light rare earth elements, lanthanum (La), cerium (Ce), praseodymium (Pr), neodymiun (Nd), samarium (Sm)
NACE	Nomenclature of Economic Activity Codes
Nb	Niobium
Mn	Manganese
Mt	Million tonnes
NEA	National Energy Authority of Iceland

NGU	Geological Survey of Norway
NordMin	A Nordic network of expertise and research focusing on sustainable nonenergy raw materials, active during 2013–2017
Ni	Nickel
Os	Osmium
P	Phosphorus
Pd	Palladium
PGE	Platinum Group Elements; this equals to PGM
PGM	Platinum Group Metals (Pt, Pd, Rh, Ru, Ir, Os)
Pt	Platinum
PV	Photo-voltaic or photovoltaic: conversion of light into electricity using semiconducting materials; essential part of the function of the solar panels
REE	Rare Earth Elements; the metals included are listed at HREE and LREE, above
Rh	Rhodium
RM	Raw material
RU	Reykjavik University
Ru	Ruthenium
Sb	Antimony
SGU	Geological Survey of Sweden
Si	Silicon
SR	Supply Risk
Ta	Tantalum
Ti	Titanium
USGS	United States Geological Survey
V	Vanadium
W	Tungsten (Wolfram)
Zn	Zinc

Appendix 2. CRM production and resource statistics.

Table A1

	Antimony	Baryte	Beryllium	Bismuth[6]	Cobalt	Copper
Mine production (tons of commodity)[1]						
- Global[2]	153,000	7,500,000	240	?	140,000	20,000,000
- Finland	0	0	0	0	1,559	36,278
- Greenland	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0
- Norway	0	0	0	0	0	0
- Sweden	0	0	0	0	0	99,332
- Nordic, total	0	0	0	0	1,559	135,610
Main global producers (2020)[2,3]	CNA, RUS, TAZ	CNA, INA, MOR	USA, CNA	CNA, LAO	DRC	CHI, PER, CNA
Nordic smelter and refinery production (tons of commodity)[1]						
- Finland	0	0	0	0	15,148	148,438
- Greenland	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0
- Norway	0	0	0	0	4,354	21,962
- Sweden	0	0	0	0	0	226,000
- Nordic, total	0	0	0	0	19,502	396,400
Global smelter and refinery production (tons of commodity)[5]	140,000	-	240	17,000	136,000	25,000,000
Resources (tons of commodity)[1,4]						
- Global[2]	1,900,000	740,000,000	>100,000	?	25,000,000	2,100,000,000
- Finland	2,554	0	294	0	453,543	4,820,000
- Greenland	3,780	592,500	65	0	0	72 730
- Iceland	0	0	0	0	0	0
- Norway	0	0	630	0	11,867	1,882,600
- Sweden	22,054	0	0	677	24,271	11,768,000
- Nordic, total	28,388	592,500	989	677	489,681	18,543,330
Assumed additional resources, qualitative information only						
- Finland	Yes	Yes	Yes	No	Yes	Yes
- Greenland	Yes	Yes	Yes	Yes	Yes	Yes
- Iceland	No	Yes	No	No	No	Yes
- Norway	Yes	yes	Yes	yes	yes	Yes
- Sweden	yes	yes	yes	yes	yes	yes

1 2020 data; source of information are the respective national mining registries
2 USGS 2021. Mineral commodity summaries 2020. U.S. Geological Survey. 204 p. https://doi.org/10.3133/mcs2020
3 One to three largest producers, only those with >10 % share of global production. Abbreviations: BRA = Brazil, BUR = Myanmar, CHI = Chile, CNA = China, DRC = Democratic Republic of Congo, INA = India, LAO = Laos, MOR = Morocco, MOZ = Mozambique, RSA = South Africa, RUS = Russia, TAZ = Tajikistan
4 Both CRIRSCO-compliant and non-compliant resources, assumed submarine resouces are excluded
5 Co (BGS 2019), Cu (USGS 2020), not relevant for baryte
6 Bismuth is only recovered as a byproduct from major metal ores, rarely included into mineral resource estimates, and nowhere mined as a target metal. Hence, mine production nor global resources are known, and in the table row 'Main global producers' the countries indicated for Bi are the main refinery producers of the Bi. Global resources were assumed at about 700,000 t about 10 years ago; this figure should be taken as an imprecise and a conservative value.

Table A2

	Fluorspar	Gallium[7]	Germanium[7,8]	Hafnium[7]	Indium[7]	Lithium	Manganese	Nickel
Mine production (tons of commodity)[1]								
- Global[2]	7,600,000	n.a.	n.a.	n.a.	n.a.	82,000	18,500,000	2,431,500
- Finland	0	0	0	0	0	0	0	41,429
- Greenland	0	0	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0	0	0
- Norway	0	0	0	0	0	0	0	0
- Sweden	0	0	0	0	0	0	0	0
- Nordic, total	0	0	0	0	0	0	0	41,429
Main global producers (2020)[2,3]	CNA, MEX, MON	CNA	CNA, RUS	FRA, USA	CNA, KOR	AUS, CHI, CNA	RSA, AUS, GAB	IND, PHL, RUS
Nordic smelter and refinery production (tons of commodity)[1,10]								
- Finland	0	0	0	0	0	0	0	90,873
- Greenland	0	0	0	0	0	0	0	0
- Iceland	0	?	0	0	0	0	0	0
- Norway	0	0	0	0	0	0	490,000	92,132
- Sweden	0	0	0	0	0	0	0	0
- Nordic, total	0	0	0	0	0	0	490,000	183 ,005
Global smelter and refinery production (tons of commodity)[5,10]	-	300	130	70	900	<80,000	?	2,500,000
Resources (tons of commodity)[1,4]								
- Global[2,6]	5,000,000,000	>1,000,000	>35,000	>1,000,000	356,000	86,000,000	17,000,000,000	300,000,000
- Finland	0	0	0	0	0	74,800	4,753,000	4,960,000
- Greenland	250,000	21,300	0	1,100,000	0	210	0	0
- Iceland	0	0	0	0	0	0	0	0
- Norway	1,160,000	0	0	0	0	0	0	108,000
- Sweden	2,828,170	0	0	6,741	0	3,240	5,934,700	2,568,000
- Nordic, total	4,238,170	21,300	0	1,106,741	0	78,250	10,687, 700	7,636,000
Assumed additional resources, qualitative information only								
- Finland	No	Unknown	Unknown	Yes	Unknown	Yes	Yes	Yes
- Greenland	Yes	Yes	Yes	Unknown	Yes	Unknown	No	Yes
- Iceland	Yes	No	No	No	No	Unknown	Unknown	No
- Norway	Yes	Unknown	Yes	Unknown	Unknown	Unknown	Yes	Yes
- Sweden	yes	Unknown	Unknown	Yes	Unknown	Yes	Yes	Yes

1 2020 data; source of information are the respective national mining registries,
2 USGS (2021); for Ge, Hf and In only refinery production is known, as only small percentage of these byproduct metals are recovered from their host ores
3 One to three largest producers, only those with >10 % share of global production. Abbreviations: AUS = Australia, CHI = Chile, CNA = China, GAB = Gabon, IND = Indonesia, KOR = South Korea, MEX = Mexico, MON = Mongolia, PHI = Philippines, RSA = South Africa, RUS = Russia
4 Both CRIRSCO-compliant and non-compliant resources, assumed submarine resouces are excluded
5 Not relevant for fluorspar. Li: refineries consumed less than what the mines produced (public information is not precise). Ni: refinery and smelter production is from BGS (2021)
6 Ga: >1 Mt in bauxite only, resources is zinc ores not known; Mn data is from Cannon et al. (2017); In data is from Werner at al. (2017)
7 Data main main producing countries for Ga, Ge, Hf and In relate to refinery production, as mine production data are not available. Ga rescovery at Icelandic aluminium smelters is not known.
8 Refinery production includes both primary (from zinc concentrates) and secondary (scrap) production; the global Ge resource (Latunussa et al. 2020) should be regarded as conservative
9 Includes ferromanganse and silicomanganese. Data from by far the largest Mn alloy producer, China, is no available (rest of the world produced abput 4.4 Mt Mn alloys in 2019)
10 Hf production is an estimate, as the trade is not transparent
11 Global Hf resources roughly estimated from the global zirconium resources using the conservative ratio Hf/Zr = 1/50. Total resources are probably larger.

Table A3

The REE are listed in three columns: Y is included into the HREE content, and the REE (total) includes also those cases, where there is no information to split into LREE and HREE

	LREE	HREE	REE (total)	Graphite	Niobium	Palladium	Platinum	Rhodium
Mine production (tons of commodity)[1]								
- Global[2]	?	?	206,400	1,100,000	78,000	210	170	23.5
- Finland	0	0	0	0	0	0.858	1.276	0
- Greenland	0	0	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0	0	0
- Norway	0	0	0	10,000	0	0	0	0
- Sweden	0	0	0	0	0	0	0	0
- Nordic, total	0	0	0	10,000	0	0.858	1.276	0
Main global producers (2020)[2,3]	?	CNA, BUR	CNA, USA, BUR	CNA, MOZ, BRA	BRA	RUS, RSA, CAN	RSA, RUS, ZIM	RSA, RUS, ZIM
Nordic smelter and refinery production (tons of commodity)[1]								
- Finland [7]	0	0	0	0	0	not known	not known	not known
- Greenland	0	0	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0	0	0
- Norway	0	0	0	10,000	0	0	0	0
- Sweden	0	0	0	0	0	0	0	0
- Nordic, total	0	0	0	10,000	0	0	0	0
Global smelter and refinery production (tons of commodity)[5]				-	?	356	263	35.6
Resources (tons of commodity)[1,4]								
- Global[2,6]	?	?	411,000,000	800,000,000	83,800,000		>100,000	
- Finland	35,061	8,664	51,700	1,276,900	123,000	587.3	265	3.6
- Greenland	?	?	34,792,000	891,300	6,467,000	271	22	0
- Iceland	0	0	0	0	0	0	0	0
- Norway	?	?	611,300	17,985,000	22,100	0.671	0.283	0
- Sweden	108,990	102,018	211,000	10,500,766	0	0.393	0.092	0
- Nordic, total	144,051	110,682	35,666,000	30,653,966	6,612,100	859	287	3.6
Assumed additional resources, qualitative information only								
- Finland	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Greenland	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Iceland	No	No	No	No	No	No	No	No
- Norway	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Sweden	Yes	Yes	Yes	Yes	Yes	Unkown	Unkown	Unkown

1 2020 data; source of information are the respective national mining registries
2 USGS (2021), except Nb and Rh which are 2018 data from Latunussa et al. (2020) and 2019 data by Johnson Matthey (2020), respectively
3 One to three largest producers, only those with >10 % share of global production. Abbreviations: BRA = Brazil, BUR = Myanmar, CHI = Chile, CNA = China, DRC = Democratic Republic of Congo, MOZ = Mozambique, RSA = South Africa, RUS = Russia, ZIM = Zimbabwe
4 Both CRIRSCO-compliant and non-compliant resources, assumed submarine resouces are excluded
5 2019 data. Not relevant for graphite. Nb: no data. PGMs: demand by all industries (Johnson Matthey 2020).
6 Global REE resources by Zhou et al. (2017); Nb: 2018 data; PGMs: jointly >100,000 t of which Pd and Pt cover perhaps 90 %
7 Platinum group metals are recovered at nickel and copper refineries, but their amounts have been reported

Table A4

	Phosphorus[7]	Scandium	Silicon metal[10]	Tantalum	Titanium	Tungsten	Vanadium
Mine production (tons of commodity)[1]							
- Global[2]		?	2,500,000	1,700	2,400,000	84,000	86,000
- Finland	182,620	0	0	0	0	0	0
- Greenland	0	0	0	0	0	0	0
- Iceland	0	0	0	0	0	0	0
- Norway	0	0	170,000	0	189,000	0	0
- Sweden	0	0	0	0	0	0	0
- Nordic, total	182,620	0	170,000	0	189,000	0	0
Main global producers (2020)[2,3]	CNA, MOR, USA		CNA	DRC, BRA, RWA	CNA, AUS, CND	CNA	CNA, RUS, RSA
Nordic smelter and refinery production (tons of commodity)[1,8]							
- Finland	-	0	0	0	0	0	0
- Greenland	-	0	0	0	0	0	0
- Iceland	-	0	36,000	0	0	0	0
- Norway	-	0	240,000	0	21,582	0	0
- Sweden	-	0	0	0	0	0	0
- Nordic, total	-	0	276,000	0	21,582	0	0
Global smelter and refinery production (tons of commodity)[5,8]	-	15	2,500,000	1,700	-	?	105,000[11]
Resources (tons of commodity)[1,4,7]							
- Global[2,6,7]		>6,000,000[9]	?	>140,000	690,000,000	7,000,000	63,000,000
- Finland	219,000,000	2,180	minor(?)	477	17,300,000	2,300	1,085,500
- Greenland	358,000	0	2,800,000	1,093,147	57,400,000	819	1,372,700
- Iceland	0	0	0	0	0	0	0
- Norway	14,000,000	50,000	28,300,000	0	99,400,000	2,625	318,360
- Sweden	26,900,000	0	522,600	68	6,100,000	1,770	4,161,850
- Nordic, total	260,000,000	52,180	31,622,600	1,093,692	180,200,000	7,514	6,938,410
Assumed additional resources, qualitative information only							
- Finland	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Greenland	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Iceland	No	No	No	No	Yes	No	No
- Norway	Yes	Yes	Yes	No	Yes	Yes	Yes
- Sweden	Yes	Unknown	Yes	Yes	Yes	Yes	Yes

1 2020 data; source of information are the respective national mining registries
2 BGS (2021), USGS (2021); silicon metal is derived from ultra pure quartz for which global mine production is not available
3 One to three largest producers, only those with >10 % share of global production. Abbreviations: AUS = Australia, BRA = Brazil, CNA = China, CND = Canda, DRC = Democratic Republic of Congo, MOR = Morocco and Western Sahara, RSA = South Africa, RUS = Russia, RWA = Rwanda
4 Both CRIRSCO-compliant and non-compliant resources, assumed submarine resouces are excluded
5 Silicon metal: demand by all industries, 2012-2016 estimate (Latunussa et al. 2020). Tantalum: estimate only available.
6 Only global reserves are known for tantalum, resources are supposed to be much larger
7 Calculated from the P mineral apatite production and resources
8 Demand of pure element is minor compared to total demand of the mineral for P and Ti; the exact total refinery production data is not available, but are assumed to be close to the mined volumes.
9 Scandium is only recovered as a byproduct from major metal ores, rarely included into mineral resource estimates, and nowhere mined as a target metal. Hence, the total mine production is not known. The total global resources are assumed by Wang et al (2021) to 6,144,000 tons of Sc metal.
10 Raw material for silicon metal is produced from quartz resources which also are used in other purposes for larger tonnages than what is used for silicon metal production. Hence figures for global production are uncertain and resourse cannot be given, but he resources are assumed to be very large. Mine production is listed as tons of quartz with Si metal as end use
11 Estimated figure. About 20 % of vanadium demand is covered from secondary sources: fly ash, petroleum residues, alumina slag, and spent catalysts.

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