Report

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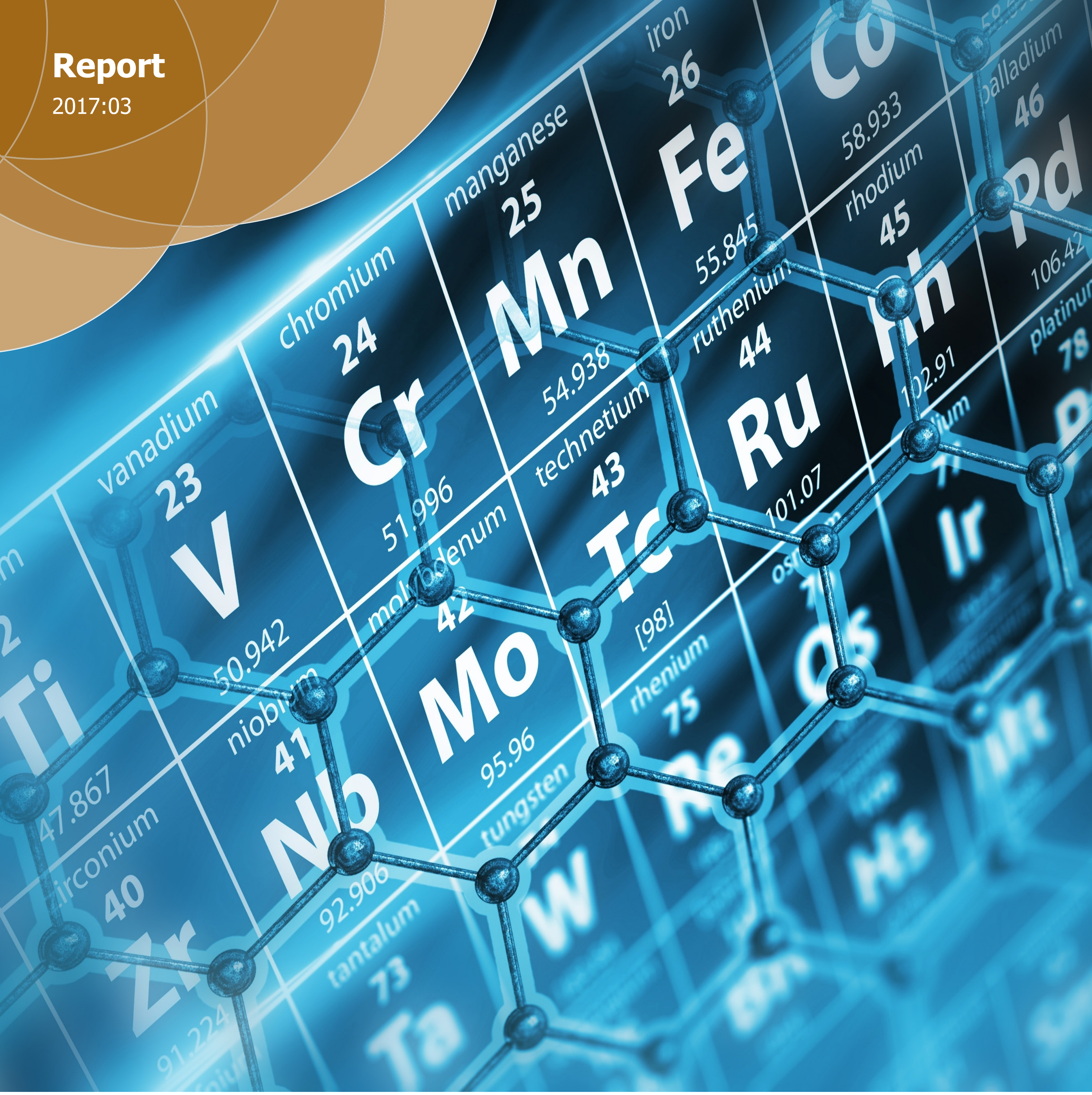

Innovation-critical metals & minerals from extraction to final product

– how can the state support their development?

In this report, Growth Analysis identifies future needs for innovation-critical metals and minerals. In addition, we provide information regarding what might be required in order for the entire production chain – from extraction to finished product – to be located in Sweden.

growth analysis

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Preface

The Swedish government has tasked Growth Analysis with identifying future needs for metals and minerals that are critical for new environmental and technological innovations, defined in this report as "innovation-critical metals and minerals". In addition, the project involved analysing and providing information regarding what might be required in order for the entire production chain – from extraction to finished product – to be located in Sweden.

Both of these issues are analysed in this report. In addition, we discuss some policy routings for the state's role in the development of value chains with regard to innovation-critical metals and minerals.

Copenhagen Economics contributed two background reports, including data and interviews, that can be downloaded in full from the Growth Analysis website.

A reference group comprising representatives from the Association of Swedish Engineering Industries, Luleå University of Technology, the Geological Survey of Sweden, and Vinnova was linked to the project.

Growth Analysis' project group consisted of the analyst Ilka von Dalwigk, Head of Department Enrico Deiaco, and analyst Tobias Persson, who also acted as project manager.

Östersund, Sweden, October 2017

Sonja Daltung
Director General
Growth Analysis

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Summary

The availability of innovation-critical metals and minerals is essential for the functioning of modern energy, environmental, and technological innovations, and these metals and minerals are becoming increasingly important. They are found in all electronics, solar cells, wind turbines, and batteries – essentially, all technologies that are key to the transition to a more environmentally sustainable society. That said, their extraction and refinement can give rise to significant environmental problems. Several innovation-critical metals and minerals are currently being extracted in just a few countries; for example, roughly 85 per cent of all rare earth elements come from China.

This report looks at two issues that the Swedish government commissioned Growth Analysis to analyse. The first was to outline future needs for innovation-critical metals and minerals. The second was to look at what the Swedish state can do to improve the conditions for the development of an entire Swedish production chain for innovation-critical metals and minerals, from extraction to finished product.

Sweden has the physical potential for the extraction of innovation-critical metals and minerals

Within this project, the term "environmental and technological innovations" has been defined as innovations that have the aim of reducing environmental impact by way of increased resource efficiency, the use of renewable energy, and recycling of raw materials. Using this definition, five technologies have been selected that are of particular importance – permanent magnets, batteries, special alloys, fuel cells, and solar cells. Permanent magnets have a special status in this context because they are a fundamental technology in an electrified society. This also implies that modern technology is particularly dependent on the availability of rare earth elements. Consequently, a society with electrified vehicles powered by renewable electricity is impossibility without access to rare earth elements.

Several innovation-critical metals and minerals can be extracted in Sweden, including rare earth elements and graphite. In addition, there is potential for the extraction of lithium, nickel, and tungsten, and to certain extent cobalt. This means that Sweden has an interesting geological potential with regard to the rapidly growing demand for lithium-ion batteries, permanent magnets for electronics, and many special alloys within the steel industry. This geological potential exists not only in new mines, but also in mining waste from old or existing mines. The physical extraction volume of several of the metals and minerals needed to produce fuel cells and solar cells is, however, not especially high in Sweden. In addition, even if extracting these as part of a recycling programme of end products were technically possible, it would not be profitable because there are only very small quantities of these metals and minerals contained in these products, which are developing rapidly in terms of both their design and choice of materials.

Appropriate state initiatives are defined by potential and challenges

In our analysis, we have identified comparative advantages within three value chains – rare earth elements, lithium-ion batteries, and special alloys containing tungsten. Because Sweden's geological potential is good or very good for all three of these value chains, measures that facilitate mining in general are key to their development.

In the case of rare earth elements and special alloys containing tungsten, the assessment is that Sweden should not introduce measures beyond those that facilitate mining in general. Rather, rare earth elements should be seen from a European perspective, where Swedish companies can find and develop a position within a European value chain. We find, however, that even a European value chain could prove difficult to establish because it would likely struggle to compete commercially with existing Chinese clusters. There is a significant market risk, and given that security of supply is a necessity, the state would need to implement measures to mitigate this risk.

The state could bolster the development of a value chain for lithium-ion batteries, and there are possible spillover effects in the development of this value chain. Swedish battery manufacturing would create an incentive for the extraction of graphite, lithium, and cobalt, in addition to having the potential of being integrated vertically with battery manufacturing and consequently lead to potentially lower production costs.

General measures to improve the attractiveness of the mining industry

General government or state measures to improve the attractiveness of the mining industry are vital for any value chains that might be developed around the extraction of innovation-critical metals and minerals. These are measures whose primary purpose is to reduce the institutional risk that is deemed to have increased in Sweden in recent years. This includes inertia in the form of political conflicts between economic, social and environmental objectives, as well as lengthy decision-making processes with regard to spatial planning and the granting of mining concessions. The tendency has been that the state and its authorities have chosen a direction that minimises rather than manages risk. This results in decision makers seeking ever more data and information to create the sense of having a complete assessment of the future impact of a mine. This approach results in protracted and unpredictable permitting procedures that hamper innovation and entrepreneurship.

To change this tendency, the state can:

- *Include benefits in permitting procedures*. The application for a mining concession includes requirements for assessing the impact on the environment and cultural heritage of the mining site. However, the process has no requirements or tools for how to weigh in the benefits of a mine. Consequently, the application should also require an assessment of the benefits to the local community and other community stakeholders, as well as a description of measures that would result in the realisation of these benefits to society. In addition, the upsides of sustainable metals and minerals in value chains need to be taken into account in the development of EU regulations, such as within Eco-design, REACH, and carbon dioxide requirements for vehicles. If these upsides are ignored in the shaping of requirements, the European engineering and manufacturing industry risks increased difficulty competing internationally.
- *Ensure expertise*. A prerequisite for sustainable mining and operations is access to expertise for companies, authorities, and courts. However, Sweden’s mining industry faces a skills drain due to retirement departures and a lack of trained students with the necessary expertise in Sweden’s specific geological conditions who can replace those who retire. More funding might be needed for basic and applied research aimed at enhancing and ensuring long-term expertise in Swedish geology.
- *Dialogue sessions to create better consensus*. There is currently a conflict between anti-mining interests and business interests. Dialogue based on knowledge is needed in

order to find a middle ground in this conflict. Consequently, the Geological Survey of Sweden (SGU) and the Swedish Environmental Protection Agency should be tasked with arranging dialogue sessions with the relevant parties, and with producing information and guidelines on how mining and environmental interests should be evaluated. Dialogue sessions on hydropower and the environmental value of waterways, arranged by the Swedish Energy Agency and the Swedish Agency for Marine and Water Management, can be used as an inspiration.

Compared with most other countries, Sweden's mining industry and electricity mix is environmentally friendly. Consequently, there is the potential for a Swedish competitive advantage that is not currently utilised to any great extent. The state can implement initiatives to improve the conditions for such a development. In order to push development in this direction, an analysis is needed to provide an understanding of the ability to create sustainable value chains by way of the labelling of metals and minerals. This involves analysing how competitiveness is affected as well as how the state can stimulate demand for products containing sustainably produced metals and minerals.

Targeted initiatives for lithium, graphite, and cobalt

Interest in the manufacture of lithium-ion batteries might serve as a springboard for the development of a cluster that also includes the extraction, refinement, enrichment, and recycling of lithium, graphite, and cobalt. Such a development should take place on commercial grounds because this would create the conditions for the long-term development of such a cluster. Should this development be initiated by the state, it risks disappearing as soon as the state ceases to support its development.

Relevant initiatives for state support include:

- Pilot, demo, and testing facilities.
- The promotion of open clusters and networks operated by commercial interests.

Sweden as a part of international value chains

For a small, open economy such as Sweden's, the starting point should be identifying where Sweden might have comparative advantages and how these can be developed. Several European countries, including Sweden, are at the forefront of the development of consumer products containing rare earth elements.

Rare earth elements might be extracted in Sweden, but the technical and industrial expertise needed for some aspects of their refinement and enrichment is lacking or in need of development. However, this expertise does exist in countries such as Estonia and France where rare earth elements are imported before being refined domestically. In order to increase the attractiveness of Swedish extraction of innovation-critical metals and minerals, the state could initiate additional international collaborations and engage in international initiatives.

1 Introduction

Metals and minerals are used everywhere in modern society, from vehicles to energy conversion, from construction to health care, and from food production to manufacturing. Innovation is a perpetual process in which raw materials are processed for specific purposes. Technological innovation over the last ten years has transformed the structure of the demand for many metals and minerals. Most of the metals needed for a transition to renewable energy such as wind power and solar cells, or for high-tech products such as computers and mobile phones, are not currently extracted in the EU. For example, China accounts for approximately 85 per cent of the global production of the rare earth elements needed in many high-tech products. Modern batteries require cobalt, for example, which is largely extracted in the Democratic Republic of Congo.

The special metals and minerals that environmental and technological innovations depend on are generally used in small quantities, but are essential to the functioning of such technologies. This is why this report refers to these metals and minerals as “innovation-critical”. Demand for many innovation-critical metals and minerals are growing by more than 10 per cent per year. This is a trend that is only expected to continue.[1] The recycling rate of innovation-critical metals is, bar a few exceptions, very low, the primary reason being the small quantities used in the end products.

1.1 The project

In October 2016, the Swedish government tasked Growth Analysis with identifying future needs for metals and minerals that are critical for new environmental and technological innovations currently being developed in Sweden and the rest of Europe. In addition, the project involved analysing and providing information regarding what might be required in order for the *entire production chain – from extraction to finished product* – of the identified environmental and technological innovations to be located in Sweden; i.e. to create added value for the metals extracted in Sweden.

Following dialogue with the government, the future *requirement* for critical metals and minerals was interpreted as a description of which metals and minerals are necessary in new environmental and technological innovations. The requirement of the project to investigate *entire production chains* in Sweden was a considerable one because Sweden is a small country where it is difficult to create entire value chains. Consequently, the question was expanded in some sections to describe initiatives that could create added value from an EU perspective; i.e. value chains that, in this context, are based on the extraction of innovation-critical metals and minerals in Sweden but with enrichment in other EU Member States.

The project can also be seen from a broader perspective with regard to the reliable supply of materials in Sweden and Europe at competitive prices. Based on this broader perspective, part of the strategy also covers the recycling of innovation-critical metals as well as the development of technology that does not require as many innovation-critical metals. Consequently, this report briefly describes some of the challenges pertaining to the recycling of innovation-critical metals.

This report is Growth Analysis’ final report for the project.

[1] Grand View Research (2016), TechSci Research (2016).

1.2 Method and delimitations

This report is based on an analysis conducted by Copenhagen Economics on behalf of Growth Analysis and expands upon our interim report *Value Chains for Innovation-Critical Metals and Minerals*, which was presented to the Government Offices of Sweden in March 2017.[2] Copenhagen Economics has done the groundwork regarding the need for innovation-critical metals and minerals and the development of value chains relating to rare earth elements and graphite. The background report is based on interviews and literature studies and has been supplemented with further interviews and literature studies, as well as quantitative data, not least to supplement the analyses regarding lithium, tungsten, and recycling. In addition the project featured a reference group comprising representatives from Vinnova, SGU, the Association of Swedish Engineering Industries, and a researcher from Luleå University of Technology.

The selection of innovation-critical metals and minerals relevant to the establishment of Swedish production chains was largely based on the list of critical raw materials produced by the EU.[3] The list is regularly updated and currently includes 20 raw materials that have been selected according to the following criteria: substantial economic importance for various key sectors, vulnerability to major supply risks, and the existence of few or no substitutes.

The project was limited to metals and minerals for environmental and technological innovations where the supply is limited and there is geological potential for their extraction in Sweden. This means that more traditional metals and minerals such as iron ore and copper were excluded from the project. Nevertheless, demand for traditional metals and minerals will also increase as a result of new environmental and technological innovations. The amount of critical metals and minerals in innovations is generally very low, and traditional metals and minerals continue to represent the lion's share of material consumption.

Our analysis starts with identifying Swedish strongholds in a value chain based on mining a deposit in Sweden. Sweden is deemed to be in a strong position where commercial interest exists, where there is advanced academic expertise in the field, and where the cost of input materials is considered to be competitive. The innovation-critical metals and minerals deemed to have significant potential for development are graphite, lithium, and tungsten, as well as rare earth elements that are specifically referred to in the report.

[2] Copenhagen Economics (2017)
[3] European Commission (2010, 2014, and 2017a)

Definitions

Critical materials and raw materials

Two criteria govern whether a material or raw material is critical – its economic importance and its availability. The term is used broadly, and critical raw materials might include biotic (e.g. pulpwood) and abiotic (e.g. metals and minerals) raw materials.

Strategic materials and raw materials

The term strategic raw materials is used for metals and minerals that are required for a country's national defence and which are seen as a key component in national security policy.

Innovation-critical metals and minerals

Innovation-critical metals and minerals are a selection of metals and minerals that are considered critical for environmental and technological innovations.

Metals

A metal is an element or an alloy (a material with metallic properties and consisting of two or more elements, at least one of which is a metal). Metals may, depending on their physical and chemical properties, be categorised as ferrous metals, non-ferrous metals, precious metals, or special metals. Rare earth elements are included in the special metals category.

Rare earth elements

The collective term "rare earth elements" relates to a group of 17 metallic elements that are chemically and physically similar and which are used in small quantities for special properties. They include lanthanides, yttrium, and scandium. Rare earth elements are difficult to find in concentrations that can be extracted economically.

Value chains for innovation-critical metals and minerals

The simplified value chains for the identified innovation-critical metals and minerals are based on the following:

Deposits and extraction of raw materials: Mining includes all activities carried out in or close to the deposit in order to extract the raw material in question. Because many metals and minerals are not present in their pure form but as ores or as small volumes within larger volumes of rock, the deposits need to be mined, crushed, and sometimes ground down into smaller fractions prior to the initial enrichment and subsequent transport.

Enrichment of raw materials: This stage involves several process steps designed to further enrich the metals and minerals to make them usable in the final products. The enrichment and separation processes are often highly specialised and require specialist expertise.

Applications in end products: This stage involves the production of the end product that forms part of the environmental or technological innovations.

Recycling: This final stage covers all efforts to recycle innovation-critical metals and minerals both from mining waste and from consumer products. This includes all steps to recycle the raw material.

2 Availability of innovation-critical metals and minerals in the rest of the world

In order to assess the areas in which Sweden is well positioned to develop value chains based on the extraction and refining of innovation-critical metals and minerals, we need to define "environmental and technological innovations". We have chosen to define them as innovations that have the aim of reducing environmental impact through improved resource efficiency, the use of renewable energy, and the recycling of raw materials. Against this background, five relevant technologies were analysed that we consider to still have considerable potential for technological innovation within the following fields – permanent magnets, batteries, special alloys, fuel cells, and solar cells (Growth Analysis, 2017). These are technologies that are vital to innovations relating to information and communication technology, modern electronics, vehicles, and the supply of renewable energy (Figure 1). Permanent magnets have a special status in this context because they are a fundamental technology used in all of these final products. This also implies that modern technology is particularly dependent on the availability of rare earth elements. Consequently, a society with electrified vehicles powered by renewable electricity is an impossibility without access to rare earth elements.

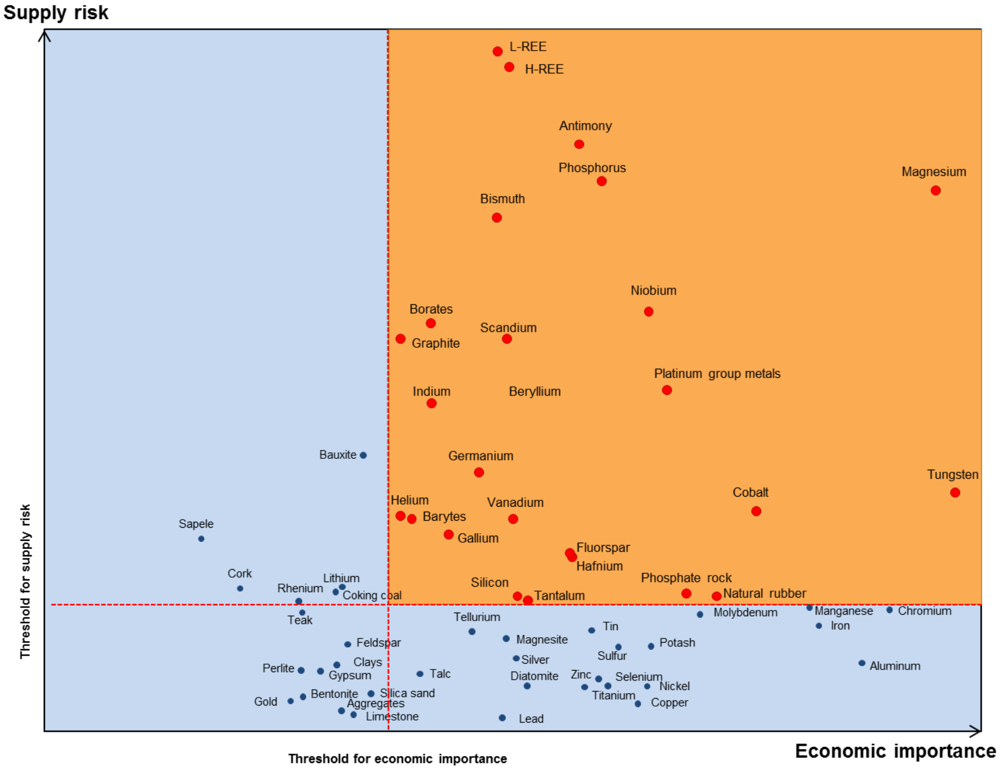
Figure 1 Required innovation-critical metals and minerals. Rare earth elements are highlighted in yellow.

Environmental or technological innovation	Applications	Required innovation-critical metals and minerals, REEs highlighted in yellow
Permanent magnets	Electric motors Wind turbines Speakers	*Neodymium (Nd), dysprosium (Dy), praseodymium (Pr), terbium (Tb)*, gallium (Ga)
Lithium-ion batteries	Vehicles Electronics Energy storage	Graphite(C), lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), vanadium (V)
Special alloys	Vehicles Refineries Condensing power plants	Cobalt (Co), tungsten (W), nickel (Ni), chromium (Cr), molybdenum (Mo),
Fuel cells	Vehicles Electronics Energy storage	Platinum (Pt), platinum group metals (PGM), graphite (C)
Solar cells	Solar cells	Silicon (Si), molybdenum (Mo), beryllium (Be), germanium (Ge), gallium (Ga), indium (In)

2.2 Critical metals and minerals – a familiar concept

The growing demand for raw materials coupled with a heavy dependency on imports was brought to light early on in the EU. To ensure a sustainable supply of these materials, the European Commission embarked on two action plans – the Raw Materials Initiative, which was adopted in 2008, followed by the European Innovation Partnership on Raw Materials in 2012.[4]

Figure 2 The EU's 2017 list of critical raw materials based on their economic importance and supply risk



Source: European Commission (2017c) Study on the review of the list of Critical Raw Materials 2017, Executive summary.

Within the context of the Raw Materials Initiative, the Commission has published several lists of critical materials. The first was published back in 2011 and identified 14 materials as being critical for European society and welfare. The analysis was based on a selection of 41 materials outside the fields of energy and food. The list was revised in 2014 using the same method as in 2011 and was expanded to include 54 materials, including seven new abiotic materials and three biotic materials (rubber, pulpwood, and sawn coniferous wood). The list included 20 raw materials that were deemed critical for modern society and welfare.[5]

In 2017, the list of critical raw materials was expanded to include 61 materials analysed using a new refined method.[6] Figure 2 shows the final assessment of the supply risk and

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[4] European Commission (2008) and European Commission (2012).
[5] European Commission (2014). Report on critical raw materials for the EU – Report on the ad hoc working group on defining critical raw materials.
[6] European Commission (2017a), Assessment of the methodology for establishing the EU list of critical raw materials. Background report – Study.

economic importance of the raw materials. Nine new materials (six abiotic and three biotic) were included, and 15 rare earth elements and five platinum group metals (with the exception of osmium) were analysed separately[7] (see Table 1).

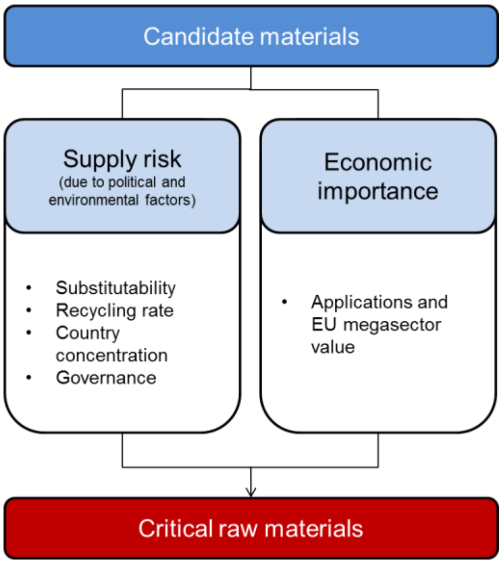
Table 1 EU lists of critical raw materials for 2011, 2014, and 2017

2011	2014	2017
Antimony	Antimony	Antimony
		Baryte
Beryllium	Beryllium	Beryllium
		Bismuth
	Borates	Borate
	Chromium	
Cobalt	Cobalt	Cobalt
	Coking coal	Coking coal
Fluorspar	Fluorspar	Fluorspar
Gallium	Gallium	Gallium
Germanium	Germanium	Germanium
		Hafnium
		Helium
HREEs	HREEs	HREEs
Indium	Indium	Indium
LREEs	LREEs	LREEs
	Magnesite	
Magnesium	Magnesium	Magnesium
Natural graphite	Natural graphite	Natural graphite
		Natural rubber
Niobium	Niobium	Niobium
PGMs	PGMs	PGMs
	Phosphate rock	Phosphate rock
		Phosphorus
		Scandium
	Silicon metal	Silicon metal
Tantalum		Tantalum
Tungsten	Tungsten	Tungsten
		Vanadium

The method used by the EU to identify whether a metal or mineral is critical (Figure 3) is based on an empirical assessment of their economic importance to the EU's industrial mega-sectors and in relation to any supply risks as quantified using the World Governance Indicator.[8]

[7] European Commission (2017b), Study on the review of the list of Critical Raw Materials Criticality Assessments. Final report.
[8] European Commission (2010): Critical raw materials for the EU

Figure 3 The EU method of assessing whether a raw material is critical



Source: European Commission (2014)

No standardised methodology exists for assessing what a critical raw material is. In addition to the criteria stated above, sector-specific and local conditions will also play a role. Consequently, there are some disparities between the EU critical raw materials list and other lists of critical raw materials. Materials that are important in the defence sector are sometimes designated as strategic raw materials and so do not form part of this report.

The supply risk of many critical raw materials is primarily based on the fact that the majority of their global production is confined to a limited number of countries. This concentration of production is exacerbated in part by the fact that it is difficult to find substitutes for some of these materials as well as the generally low level of recycling. Nevertheless, there are known deposits of antimony, fluorite, phosphate minerals, graphite, cobalt, platinum group elements, rare earth elements, and tungsten in Sweden. Sweden has a number of different metal and mineral deposits and a long history of mining, and it offers offer good access to infrastructure, cheap energy, and specialist support services.[9]

2.3 Arguments for state intervention

There is ongoing concern regarding the security of the supply of raw materials at competitive prices in most industrialised countries in Europe and in the United States, and this is reflected in several studies.[10] Activities aimed at the specific extraction and refining of metals and minerals that are critical for environmental and technological innovations can be justified because the extraction of these metals and minerals currently occurs in a market often lacking in competition and in countries with weak environmental legislation and high conflict levels.

Weak competition makes Sweden and many other countries that do not extract and refine several critical metals and minerals themselves vulnerable. Such vulnerability can manifest itself in the throttling of imports of critical metals and minerals. This happened in the

[9] Growth Analysis (2016)
[10] Erdman et al. (2011), British Geological Survey (2012), US Department of Defense (2013), US Department of Energy (2011).

autumn of 2010 when China stopped the export of rare earth elements to Japan for one month. Vulnerability can also manifest itself in price dumping as a way to remove new players that provide competition. In recent years, China has adopted a strategy of venturing further up value chains and not simply being a cheap source of raw materials. This development has been very rapid. An example is the way China has used concerted efforts to lead entire value chains based on the extraction of rare earth elements. In Baotou, a hub for the extraction of light rare earth elements in China, as of 2017 there is a cluster of more than 200 companies working throughout the value chain from extraction and refinement to the production of permanent magnets, special alloys, batteries, and magnetic sensors. The focus is on developing and becoming the leader of five value chains for functional materials based on rare earth elements – permanent magnets, polishing powders, luminescent materials, materials for storing hydrogen gas, and catalytic converters. Close co-operation between industry, universities, and research institutes combined with wide-scale state funding has been the key to this development. Production is very cost-efficient and is becoming increasingly automated. By way of example, between 2008 and 2015 the China Northern Rare Earth Group increased its profit margin from 17 per cent to 32 per cent. The aim is to have a profit margin of between 50 and 60 per cent by 2020.[11] Such developments not only challenge the European manufacturing industry, but also pose a risk to the European defence industry, which is dependent on critical metals.

A different perspective, which has been raised in the debate, is whether it is ethically justifiable not to extract critical metals and minerals if doing so reduces the need to import them from countries with weak environmental legislation or where there are conflicts and a disregard for human rights. The export of critical metals and minerals can be used to fund wars and can be a contributing factor in civil war. In March 2017, the EU adopted legislation to make it harder for armed groups to fund their activities through the sale of conflict metals. Regulation (EU) 2017/821, which enters into force in 2021, will force EU Member States to identify where imported metals and minerals come from and to confirm that their imports are not financing armed conflicts.

An additional perspective is that innovation-critical metals and minerals are limited resources. Estimates by Sverdrup (2017), based on known resources, show that deposits will run out within a matter of decades. Yet, in reality, the exploration of global geological resources is inadequate. Consequently Sverdrup's estimate might be used to substantiate the need for better mapping of geological potential, as well as for measures to increase the reuse and recycling of metals and minerals.

In the following sections, these arguments will not be discussed further. The starting point is instead that the state should take action.

[11] Rølmer S., (2017).

3 Value chains based on extraction – what can the state do?

Since 1991 a raft of changes has been made to Swedish legislation on minerals. These include a reduction in tax on profits from mineral mining from 50 per cent to only a few per mille. Tax cuts are part of a strategy that aims to inject new life into the Swedish mining industry. The year 2013 saw the publication of Sweden's first ever minerals strategy, which had the following overarching objective: "The Swedish minerals strategy takes an integrated approach in order to create beneficial conditions and to identify opportunities and challenges so that the mining and minerals industry can grow sustainably and keep pace with the opportunities provided by today's strong international demand for metals and minerals."

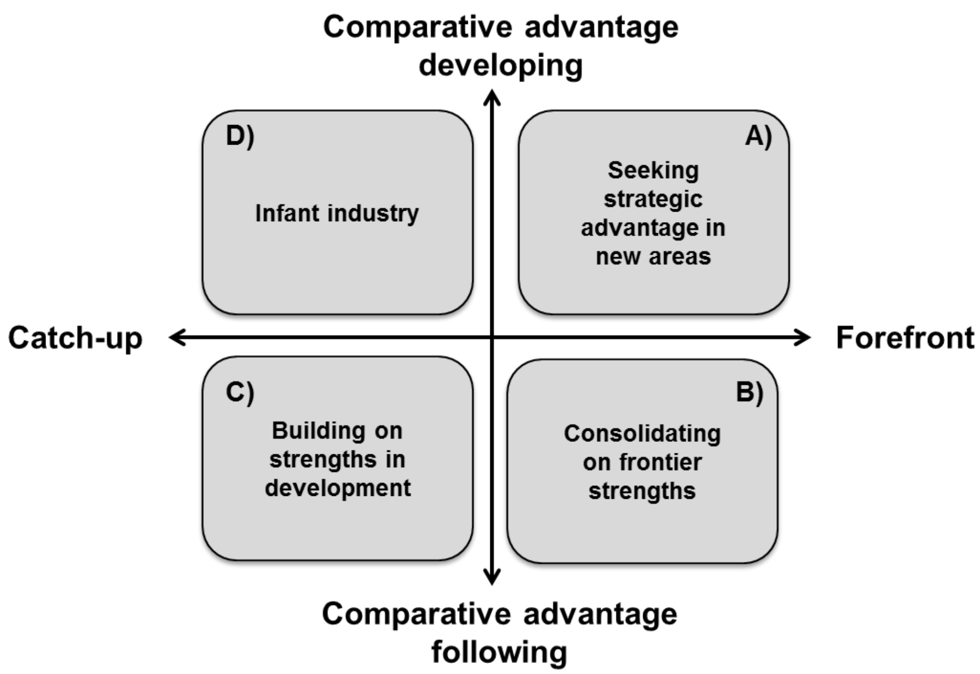
How can business and innovation policy contribute to the development of favourable conditions, especially with regard to the creation of new value chains for innovation-critical minerals and metals, and/or strengthen the value chains that already exist? Which instruments of industry and trade policy can be used? In the following sections, we present the simple framework that is used to describe and analyse the bottlenecks and risks that come with the process of establishing new and developing existing value chains.

3.1 An analytical framework

Different types of industry and trade policy can be described as shown in Figure 4. Countries that are at the forefront of technological innovation often have an industrial and innovation policy focused on the use of existing competitive advantages to build new markets (A in the figure) and/or to develop a policy with the aim of enhancing and retaining existing positions of strength (B in the figure). Countries that are not at the technological front line have other challenges and are trying to catch up with more technologically advanced countries (D in the figure) or to take advantage of being a developing country that generally enjoys lower production costs (C in the figure).

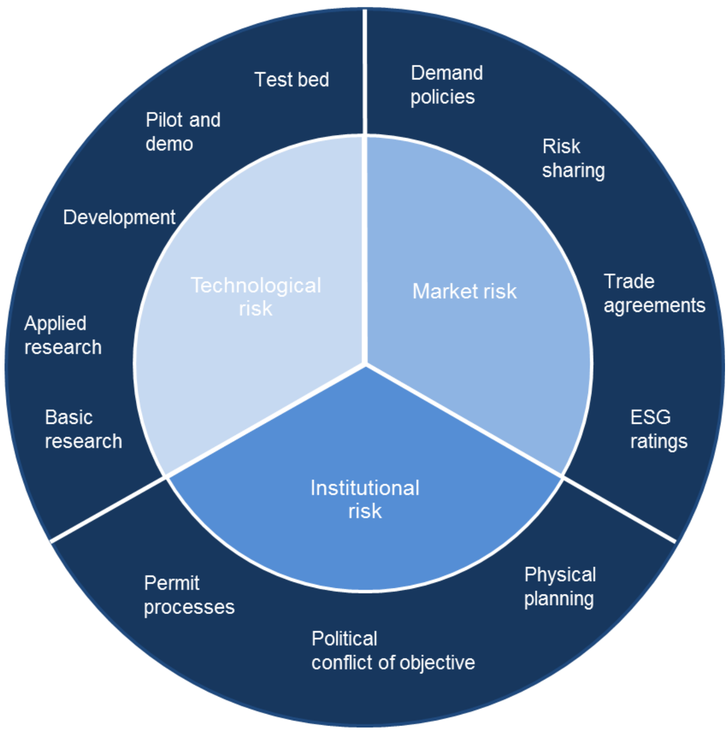
The figure can also be used to illustrate which development phase different innovation-critical metal value chains are in and what their competitive advantages are in Sweden as compared with corresponding value chains in other countries. If this competitive advantage relates to metals and minerals where Sweden already enjoys a position of significant strength within a relatively mature global market, these metals and minerals might fall in quadrant B. Other innovation-critical metals are characterised by value chains that are in their infancy or immature, both locally and globally. For instance, there might be genuine uncertainty with regard to the geological and economic potential that exists, or the value chains might be in the process of being formed and various companies are competing to find their relative positions in the emerging chains. This situation is located predominantly in quadrant A. Quadrant D is characterised by a situation in which the competitive advantage might be the significant physical availability of metals and minerals, but where companies might need temporary protection or support for their establishment and development (this usually falls under "infant industry policy"). Metals and minerals that have a strong value chain in certain countries but weak global demand fall within quadrant C.

Figure 4 Innovation policy challenges



Source: Warvick (2013)

Figure 5 Risks and examples of state measures that reduce these risks



Source: Growth Analysis

Each quadrant might contain different types of market imperfections, bottlenecks, and risks. Figure 5 provides examples of the various risks and state interventions that can be used, either individually or in combination, in order to create the conditions needed to establish new value chains or to strengthen those that already exist. It is well known that major investments in untested technology or in the green transition involve especially large risks, and often a combination of technical, market, and institutional risks.[12] One example is the state promotion of research and knowledge aimed at stimulating activities despite the risk that the results will not only benefit the private player. This reduces the risk of wasted research while at the same time making the research more accessible and more beneficial to society at large. In other words, the technical risk is reduced. Innovations that involve critical metals and minerals often face a considerable market risk due to their rapid growth and the relative immaturity of the value chains. The result of this is investments that fail to materialise despite favourable conditions. There might also be a considerable institutional risk involving things such as lengthy decision-making processes with regard to mining concessions, physical planning, or the existence of political conflicts over objectives, for example, between mining and the possible negative environmental impact of mining.

International measures for developing or honing innovation-critical value chains beyond managing the various risks are often designed as a package of short-, medium-, and long-term effects. The German strategy for electric mobility, as will be discussed in more detail in Chapter 9, is one example of this.[13] Experience suggests that if the strategy is not based on the three types of risk, there is a greater likelihood that the initiative will fail or that the public investments will result in technical and market lock-ins that might be difficult to get out of.[14] One example of this is the Swedish investment in the production of ethanol. Less than a decade ago, the state invested heavily in demonstration support for the commercialisation of biofuels from forest-based raw materials. However, this was done without implementing measures to generate demand for more advanced biofuels, and it was expected that they would be able to compete with much cheaper imported alternatives. The result was that the use of ethanol increased in Sweden, but primarily by way of imports.[15]

Against this background, in the following sections the analysis will describe the risks that exist in the various value chains. Chapter 9 then discusses various pros and cons of public intervention for each value chain.

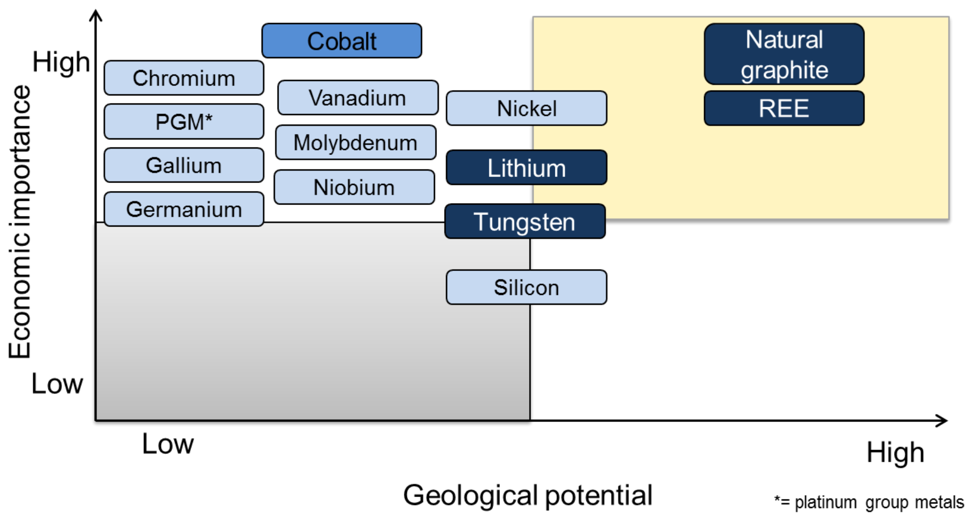
[12] Jacobsson & Bergek (2011).
[13] NPE (2017). The national strategy was formulated in 2011 by the federal government, industry, and the trade unions. The objective is for Germany to become the leading supplier of electric mobility by 2020. The strategy covers the entire value chain from batteries and electric cars to online services for electric mobility.
[14] Arthur (1988).
[15] Growth Analysis (2016a).

4 Overview of Swedish strongholds

4.1 Geological potential

The creation of a value chain around innovation-critical metals and minerals assumes that such metals and minerals can be economically extracted in Sweden, unless recycling becomes profitable or their availability is secured by way of imports. Figure 6 shows the rough geological extraction potential in Sweden for the metals and minerals used in many environmental and technological innovations.[16] The figure also shows the economic potential for these metals and minerals. This assessment is based on the evaluation made by the EU when the list of critical raw materials was updated in 2017.[17] The economic importance of each material is defined as the significance of a metal for major industrial sectors and its contribution to Europe's GDP.

Figure 6 Geological potential and economic importance of selected innovation-critical metals and minerals in Sweden



Source: Economic importance from European Commission (2017c) and geological potential from SGU (2014). Compiled by Growth Analysis.

The physical potential for several of the metals and minerals needed to produce fuel cells and solar cells is not especially good in Sweden. Several metals and minerals for these products can be found at the far left of Figure 6, that is, the known geological potential in Sweden is low. Fuel cells and solar cells are, however, developing rapidly, and the need for certain metals and minerals might change and the situation might be different in a few years. However, given the low geological potential, these two environmental innovations have not been included in this analysis. The focus has instead been on graphite and lithium for batteries, rare earth elements, and tungsten and cobalt for special alloys and metal carbide production. These value chains are analysed in more detail in Chapters 5, 6, and 7.

[16] SGU has an ongoing project that aims to demonstrate this potential in greater detail.
[17] European Commission (2017)

4.2 General conditions for value chains

The mere availability of a physical resource should not be the deciding factor in the location and development of value chains. The focus should instead be on those parts of a value chain where a country or region has a relative competitive advantage, in other words, activities where, relatively speaking, the country or region is more productive than its competitors. Consequently, it is not enough just to ensure the physical availability of a resource in order to determine the potential for Sweden to extract and recycle critical metals and minerals.

It is common for value chains to be split between countries. One example is aluminium smelting in Iceland, which has developed despite the country having no domestic availability of the mineral resource bauxite. The cost of electricity is paramount for smelting, and Iceland has an abundance of cheap electricity. This means it is profitable to ship bauxite from places as far away as Australia for smelting in Iceland.

Future value chains and the parts of them that could conceivably be located in Sweden thus hinge to a large extent on Sweden's existing strongholds. Sweden is an industrialised country, and its primary competitive advantages are most likely to be found in a variety of knowledge-intensive activities such as research and development and the service sector. There are also other strengths linked to Sweden's good availability of natural resources, mainly within risk capital financing, electricity supply, chemical innovation, and a strong automotive industry (Table 2). All of these are significant for different stages of a value chain based on critical metals and minerals. Sweden stands out in the European context due to its good access to venture capital.[18] Interviews conducted as part of this project indicate, however, that it is difficult for new mining businesses to gain access to venture capital.

Table 2 Swedish strongholds relevant for the mining cluster

Sector	**Strongholds**
Finance	Good access to venture capital
Electricity supply	Available, reliable, and cheap electricity Well-developed power grid
Chemicals	Pharmaceutical industry Chemical cluster in Stenungsund ESS in Lund
Automotive industry	Long and strong tradition in the automotive industry Research, development, and design

Source: Copenhagen Economics (2017).

The mining industry and several steps in mining-based value chains consume vast quantities of energy. Here Sweden has a competitive advantage thanks to its reliable availability of green and, from a European perspective, cheap electricity. The price of electricity is often a cost driver in the refinement and enrichment of metals and minerals, as well as in parts of the manufacturing industry. Sweden's strength in chemical research and production is relevant to critical metals and minerals because this is know-how that is necessary for the enrichment of the raw material. Many of the critical metals and minerals ultimately find their way into the automotive industry, and the fact that Sweden has several

[18] Danish Ministry of Industry, Business and Financial Affairs (2016)

vehicle manufacturers is helpful when it comes to creating a picture of future needs and the opportunity to create value chains.

The above reasoning that a country should have only the parts of a value chain where it has a competitive advantage might need to be re-evaluated if, for one reason or another, there are strong motives to reduce the country's dependence on imports. One example is the financial support the German government provides to its state lender Ungebundener Finanzkredit (UFK) in the form of a loan commitment to a tungsten mine in the UK. The purpose of this loan commitment is to ensure the German manufacturing industry's access to tungsten in the event of a crisis affecting trade in tungsten.[19] UFK guarantees (in the form of non-restricted financial loans) are an integral part of Germany's raw materials strategy, and a long-term raw material supply agreement with German buyers is a prerequisite for UFK awarding its guarantees.[20]

4.3 Sweden is an attractive mining jurisdiction, but there are challenges

From an international perspective, Sweden is an attractive mining jurisdiction.[21] Its physical potential is good, and the cost of infrastructure, labour, and energy is comparable to those of competing countries. The long-standing cross-company co-operation in the Swedish mining cluster contributes to this attractiveness. This cluster includes companies such as Atlas Copco, Sandvik, and SSAB, which have worked together for more than a century. Although there is scope for improvement, Sweden's institutional framework is relatively well designed.

4.3.1 Two dominant players

The Swedish system and mining cluster are, however, primarily shaped around LKAB's and Boliden's interests, which means that new players wanting to extract innovation-critical metals and minerals encounter difficulties when establishing themselves in Sweden.

Around 75 per cent of exploration is carried out by the two major mining companies LKAB and Boliden.[22] Compare this with around half of the exploration in several competitor countries being carried out by companies with no income from an existing mine, known as "junior exploration companies". At the very least, this has an impact on the conditions for extracting innovation-critical metals and minerals in Sweden. Because innovation-critical metals and minerals are not part of LKAB's or Boliden's core operations, there is not a great deal of knowledge regarding the availability of these specific metals and minerals.

A way to facilitate the establishment of junior exploration companies might be to involve them in a strategy for the extraction of critical metals and minerals for a Swedish value chain. One reason that some competitor countries can attract new exploration companies is that they have specific instruments that mitigate some of the risk that follows from

[19] http://www.wolfminerals.com.au/irm/PDF/1244_0/WolfreceivesrevisedcreditapprovalforGBP75million
[20] https://www.agaportal.de/main-navigation/rohstoffe-ufk-garantien/grundlagen-ufk-garantien/grundzuege-ufk-garantien
[21] Growth Analysis (2016)
[22] Copenhagen Economics (2016)

exploration being expensive and not generating revenue. A more in-depth analysis of this can be found in Growth Analysis's report on Sweden's attractiveness as a mining nation.[23]

4.3.2 Indications that permitting has become a major obstacle

Opening a new mine in Sweden requires a number of permits. This can be a lengthy process on account of the many different institutions and authorities involved. Furthermore, there are often conflicts regarding land use where there is a lack of clarity regarding how the benefits of mining should be weighed against other interests. Consequently, there is a risk of subjectivity in the permitting process, and the process depends largely on the county in which the deposit is located.[24] Long-term investments such as mines will have an effect on society and the environment for decades, but these effects cannot always be predicted in advance. New players that have not previously engaged in mining in Sweden are particularly vulnerable to these challenges because they have yet to build up the requisite expertise.

People are generally averse to risk and they fear making decisions that might have negative consequences. This can result in the responsible decision makers at the relevant authorities seeking ever more data to create the sense of having a complete assessment of the potential impact. The approach of the authorities thus tends to be to minimise risk rather than to manage risk, which also results in a prolonged permitting processes.

The Swedish government has raised the issue of the prolonged permitting processes for the mining industry and has now commissioned a study to review how to shorten decision-making processes for the establishment of mining operations without reducing or changing environmental permit requirements. As part of the project, the government will appoint reference groups consisting of business representatives.

4.3.3 Skills drain through retirement departures

Like many other sectors, the mining industry is facing a deluge of retirement departures. More than one in three people in the mining and mineral industry are expected to retire by the year 2025, and specific initiatives will be needed to ensure the availability of labour. This challenge is particularly relevant to the availability of labour with extensive knowledge of Sweden's bedrock and mineralogy. This is an area that has long been neglected despite such knowledge being key to an attractive mining industry.

Sweden has further obstacles to, and competitive disadvantages in, the emergence of value chains for critical metals and minerals, and these will be described in the next chapter.

[23] Growth Analysis (2016)
[24] Growth Analysis (2016a).

5 Rare earth elements – geological potential but weaknesses in the value chain

Permanent magnets based on rare earth elements can generate strong magnetic fields even in very small applications, making them indispensable in many modern technologies. They are also used in larger installations such as wind turbines. The value of the market for permanent magnets in 2015 was estimated at USD 13 billion, growing to USD 31 billion by 2020.[25] In addition, many special alloys contain rare earth elements.

China is the single largest producer of rare earth elements, accounting for 85 per cent of global production in 2015. China is also the only producer of rare earth elements that are represented across the entire value chain, from mining to the production of final products. The transformation of the Chinese economy in recent years has resulted in extensive initiatives to develop entire value chains.[26] This trend is likely to continue, which means that companies in other countries will probably find it harder to compete.

A longer description of rare earth elements and their applications can be found in Appendix 1.

5.1 Swedish strongholds

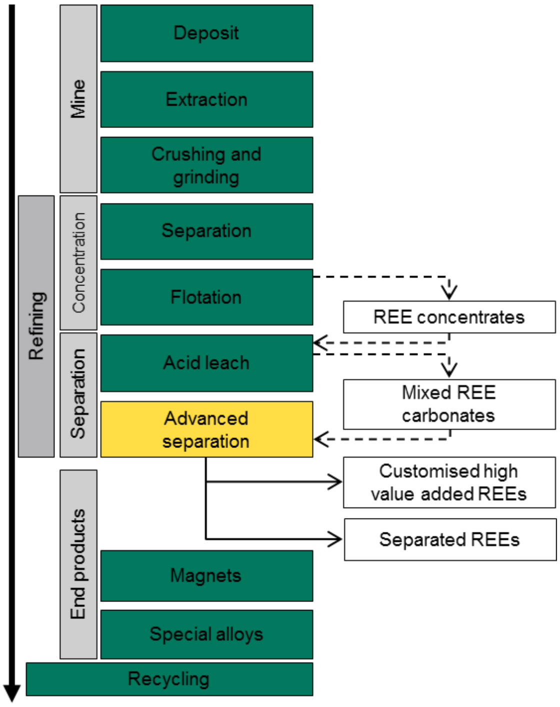
The geological conditions for the extraction of rare earth elements in Sweden are very good. The deposit in Norra Kärr on the outskirts of Gränna is of high quality and has a relatively high concentration of the most valuable rare earth elements, known as heavy rare earth elements, while their radioactive content is low. Leading Edge Materials (formerly Tasman Metals AB) has a commercial interest in mining in Norra Kärr.

Figure 7 shows the value chain for the production of rare earth elements. The early phases of ore refinement (*crushing and grinding through to primary enrichment*) are often carried out adjacent or close to the mine. The reasons are economic – to avoid the high cost of transporting the ore and mining waste because the concentration of rare earth elements in the ore is low. The majority of the ore is gangue, which has non-existent or very limited value. To keep unit costs low, it is therefore more economical to carry out refinement and/or enrichment processes that result in a first saleable product on the market adjacent to the mine, which is why this part of the value chain could be profitable in Sweden.

Another reason in favour of locating the refinement process in Sweden is the good and reliable availability of cheap electricity (from a European perspective). The price of electricity is the primary cost driver in this stage of the value chain. A third reason is access to expertise in mining operations. Finally, Chalmers University of Technology has the requisite knowledge of how to handle radioactive waste. All in all, there are very good conditions for the refinement of rare earth elements in Sweden provided that partnerships can be established with the required expertise.

[25] GWEC (2016).
[26] The People's Republic of China (2010). [27] OTC – over the counter

Figure 7 Value chain for rare earth elements



Source: Copenhagen Economics (2017). Green means that the conditions are good compared with other countries. Yellow means there are other countries that currently have better conditions. REEs = rare earth elements.

The later steps in ore refinement, including the advanced *separation* and adaptation of the rare earth elements to specific purposes, comprise a very high-tech and energy-intensive process. It is primarily the similar physical and chemical properties of the individual rare earth elements that make their continued chemical *separation* so complex. The different steps in this process do not need to be located close to the deposit. Conventional chemical separation is cost- and labour-intensive, requiring core expertise in mineralogy, geology, chemistry, and metallurgy. There are currently only a handful of facilities outside China that perform the separation of rare earth elements, two of which are located in Europe. Solvay owns a facility on the outskirts of La Rochelle in France, and Molycorp Silmet owns a facility in Estonia.

The specific skills could be developed in Sweden, but the competition is tough. The quantity of rare earth elements needed in consumer products is very low, and the price is governed by the dominant Chinese producers. Rare earth elements are not standard raw materials traded on exchanges like iron ore, gold, and copper; rather, they are traded on so-called OTC markets[27] with direct agreements between a few buyers and sellers. In 2011 China demonstrated how heavy restrictions on exports could affect the price of rare earth elements.[28] To manage supply risk, buyers and sellers of rare earth elements tend to enter into long-term agreements. Consequently, it can be difficult for a new player to gain market share. A specific example is the bankruptcy of the vertically integrated American

[27] OTC – over the counter
[28] ERECON (2015).
[29] The Molycorp Silmet plant is now owned by Neo Performance Materials and is still in operation.

producer Molycorp in 2015 as the company was unable to turn a profit following the price drop of rare earth elements after 2011.[29]

Examples of products that require rare earth elements are hybrid engines, wind turbines, telecommunications technology, lasers, solar cells, magnetic alloys, and catalytic converters. The production of these products primarily takes place in China, while the European manufacturing industry usually imports them for installation in consumer products.[30]

The knowledge created in the development of the extraction of rare earth elements can also be used in recycling rare earth elements. Currently only around one per cent of rare earth elements are recycled from discarded consumer products (see Chapter 8.2).[31] Hence Sweden could possibly play a role in the development of technologies for recycling rare earth elements.

5.2 The role of the state – the importance of the EU perspective

5.2.1 Technological risk – Sweden lacks expertise in advanced separation

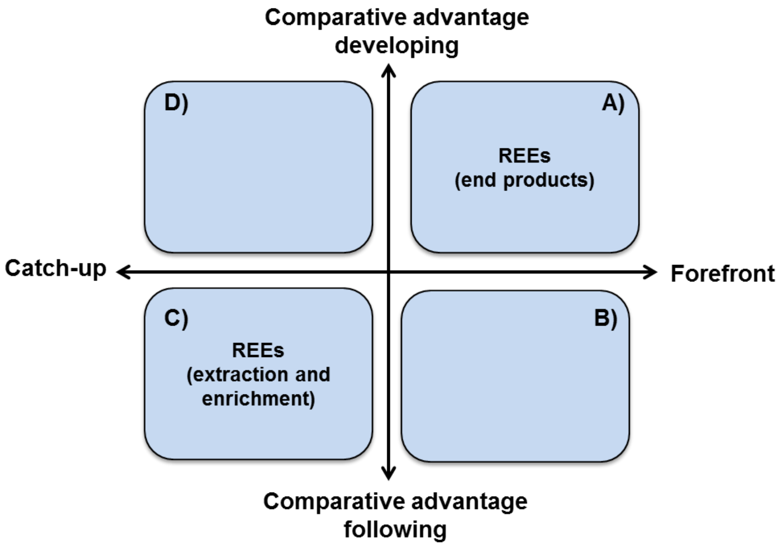
Leading Swedish industries use technologies that contain rare earth elements in their production. These include motors for electric vehicles. Sweden imports this technology, and consequently Sweden is a leader with regard to several consumer products whose technology contains rare earth elements. This means that according to the analytical framework presented in Chapter 3, final products containing rare earth elements can be categorised as being at the technological forefront and as having competitive advantages through innovation (Figure 8).

Sweden could also host other stages of the value chain for rare earth elements related to extraction and refinement leading to a first concentrate. Sweden has good geological potential as well as the knowledge needed for the refinement of the metals, but Swedish extraction would probably struggle to compete with Chinese players. The Chinese industry is very cost efficient, and rare earth elements are usually extracted as a by-product of the extraction of other commodities, which helps to keep costs down. Conversely, the Swedish deposit at Norra Kärr contains many of the heavy rare earth elements that have a high economic potential. According to Chapter 3, this stage of the value chain could be categorised in the group described as catching up with leading nations and industries.

The part of the value chain that would struggle to become established in Sweden is advanced separation. There are no Swedish players in this stage of the value chain, which is relatively complex and requires specific expertise.

[29] The Molycorp Silmet plant is now owned by Neo Performance Materials and is still in operation.
[30] National Board of Trade Sweden (2011).
[31] ERECON (2015).

Figure 8 Innovation position for rare earth metals in Sweden



A different focus could be the development of a European value chain in which separation is carried out by a partner in France or Estonia where this industry already exists. This would facilitate a European value chain from extraction to consumer products.

5.2.2 Considerable market risk as a result of Chinese dominance

A European value chain for rare earth elements is, however, associated with a considerable market risk as a result of Chinese dominance. China could use its market power to out-compete a European value chain. Consequently, the EU and its Member States would need to reduce this risk before a European value chain could be developed. At the same time, this risk should not be overcompensated. The ambition should be a European value chain that is able to compete with the Chinese cluster that is becoming increasingly more efficient. Otherwise, European consumer products will struggle to compete with Chinese products in terms of both cost and quality.

5.2.3 Measures exist to mitigate institutional risk

In order to support a European value chain for rare earth elements, the Swedish state can:

- Implement measures to mitigate the risk of mining in general in Sweden.
- Promote European co-operation with the goal of developing a European value chain.
- Create a vision for how a value chain for rare earth elements could be developed.
- Clarify the responsibility of authorities for the development of value chains based on the use of rare earth elements. This responsibility is currently shared by several authorities. SGU is responsible for extraction. The Swedish Environmental Protection Agency and the Swedish Energy Agency are responsible for recycling. Vinnova, the Swedish Energy Agency, and the Swedish Agency for Economic and Regional Growth conduct efforts relating to consumer products that depend on rare earth elements.

6 Lithium and graphite for batteries

Sweden is in the race to become the location of a new major battery factory in Europe. The company Northvolt has shown interest in setting up a battery factory in the Nordic region. There are several reasons for this interest. Perhaps the most important is the reliable availability of competitively priced electricity, which is also, from an international perspective, environmentally friendly. Electricity costs account for a large share of a battery factory's production costs. In addition, there is the availability of skilled labour and access to research and knowledge in battery technology and battery chemistry at the universities in Luleå and Uppsala, as well as at Chalmers University of Technology.

Furthermore, there are potential synergies between a battery factory and the extraction of graphite (anode) and lithium (cathode) in Sweden. There could also be synergies between the manufacture of batteries and the development of vehicles at, for example, Volvo or Scania.

Nevertheless, it should be noted that several countries are interested in establishing a battery factory. Germany in particular has plans that are currently at an advanced stage, and there is a national strategy that covers the domestic production of batteries for electric vehicles.

Value chains for graphite and lithium have reached different levels of maturity in Sweden. Consequently, the value chains for graphite and lithium in Sweden are reviewed individually below.

6.1 Swedish natural graphite

In 2015 China and India accounted for 90 per cent of global graphite production, while Europe only has small-scale production in three mines located in Austria, Germany, and Sweden.[32] Graphite consists of carbon and is primarily used in the manufacture of anodes for lithium-ion cells, in friction materials, in lubricants, and in refractory materials. It is also the only component of the promising material graphene.

After 15 years under a 'care and maintenance' set-up, the Woxna graphite mine in Dalarna was authorised to re-open in November 2016. Subsequently, the extraction of natural graphite in Sweden has proven to be not only possible, but also commercially attractive. Other deposits are currently being explored and developed by Talga Resources.

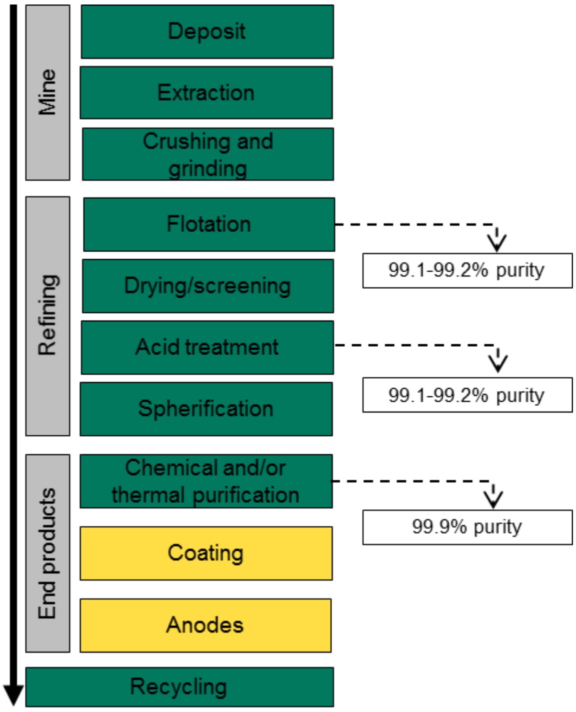
Traditionally, the first steps in ore refinement, up to drying and sorting, take place close to the mine (Figure 9). The current status of the Swedish mining industry, its strengths, and its access to chemical research all point to the same model being used in Sweden. Purity after drying and sorting is only approximately 94 per cent, which is too low to be used in, for example, the steel industry and much lower than what is required to be of battery quality. Graphite for use in batteries needs to have a purity of 99.9 per cent. To achieve this purity, the graphite is treated with acid before being ground and shaped into very small balls through the process of spherification. Although this part of the enrichment process could take place in Sweden, it could just as well take place in Central Europe.

[32] Grafitbergbau (2017), AMG Mining (2017), and Deloitte (2015).

The final production of anodes and coatings, as well as the knowledge needed for this, is currently centred in Asia. Consequently, the creation of a Swedish or European value chain for the manufacture of batteries requires attracting this specialist expertise to Europe.

Just as for rare earth elements, there is potential for developing technology to recycle graphite from batteries. Relevant research can be found at the Ångström Advanced Battery Center at Uppsala University, for example. The recycling rate for graphite is currently around 10 per cent.

Figure 9 Value chain for natural graphite



Source: Copenhagen Economics (2017). Green means that the conditions are good in Sweden compared with other countries. Yellow means there are other countries that currently have better conditions.

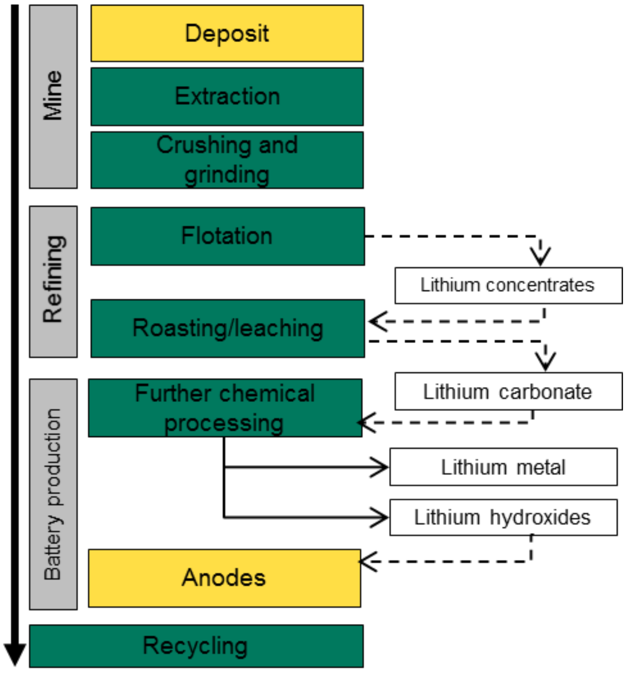
6.2 Lithium extraction lags behind in Sweden

In 2015 Chile and Australia accounted for around 80 per cent of global lithium production, and Portugal is the only European producer of lithium concentrate. High-value products such as batteries and electronics require lithium with a high level of purity, and thus lithium has a high refinement value following its extraction.

Lithium deposits have been identified in Sweden, but they are not yet well explored (Figure 10). Leading Edge Materials holds an exploration licence for Bergby between Hudiksvall and Gävle, while an Australian mining company, Dakota Mining, has been authorised to conduct test drilling for lithium close to Axmarby. At present, the economic feasibility and profitability of lithium extraction in Sweden is uncertain because mining lithium from a hard rock deposit instead of brine generally comes at a higher cost.

After extraction, a lithium concentrate is produced, which is the first saleable, but relatively low-value, product. The refinement of lithium into lithium carbonate or lithium hydroxide from hard rock is a very energy-intensive, acid-based process. New facilities are currently being constructed in Australia, Argentina, Chile, and Canada, which proves that industrialised countries can be competitive in this stage of the value chain. The same should be true of Sweden, not least thanks to its relatively low electricity prices.

Figure 10 Value chain for lithium (from hard rock)



Source: Copenhagen Economics (2017). Green means that the conditions are good in Sweden compared with other countries. Yellow means there are other countries that currently have better conditions.

6.3 Value chains for lithium and graphite would support a battery factory

The use of lithium-ion batteries is growing rapidly, and Sweden is currently in the race to become the home of a major lithium-ion battery factory. China, Japan, and South Korea dominate production (around 88 per cent of production in 2015), and they also account for much of the production of cathodes and anodes, which account for a sizeable share of the production cost of a lithium-ion battery. Chung et al. (2016) have estimated that 32 per cent of the cost of production comes from the production of cathodes and 11 per cent from the production of anodes. Lithium is present in the cathodes of these batteries, while graphite is present in the anodes.

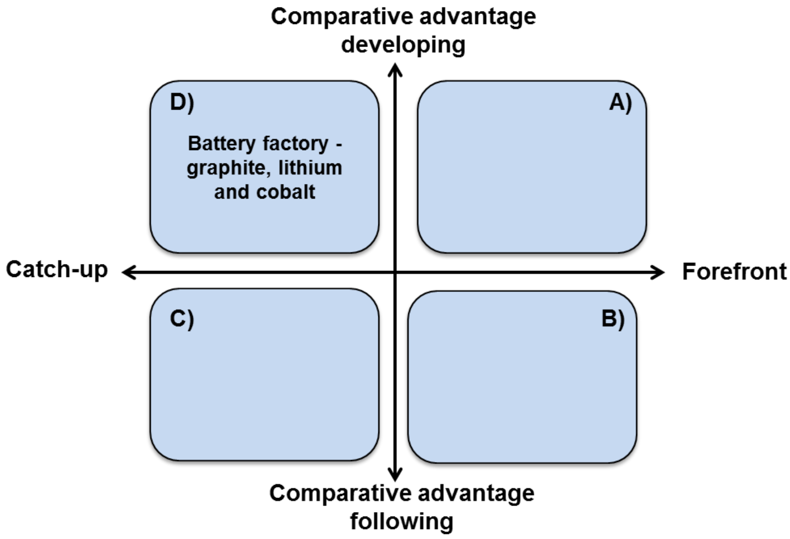
Accordingly, there are potential synergies between a battery factory and the extraction of lithium and graphite. In other words, domestic extraction of lithium and graphite would likely boost the competitiveness of a Swedish battery factory. At the very least, the knowledge needed for the extraction, refinement, and enrichment of lithium and graphite would also be needed for battery production. The physical proximity and understanding of this interdependence could also lead to new business models that mitigate the risks through co-location in Sweden.

Additionally, a battery factory might justify a greater interest in the extraction of lithium and graphite rather than vice versa. However, until such extraction becomes sufficient, much of the lithium and graphite needed for battery production is likely to be imported into Europe, and ultimately Sweden, perhaps in the form of prefabricated cathodes and anodes.

6.4 The role of the state relating to graphite and lithium

A Swedish value chain for the extraction, refinement, enrichment, and production of lithium-ion batteries would have several competitive advantages. At the same time, there are already countries and industries that have established solid expertise that is driving innovation in this area. This means that a Swedish value chain would most likely fall in quadrant D in the figure as described in Chapter 3 (Figure 11).

Figure 11 Innovation position for lithium-ion batteries in Sweden



Sweden could possibly commence production of lithium-ion batteries within the next few years as a result of Northvolt's plans. A key motivation for this is the low price of electricity and the Swedish mix of electricity being relatively environmentally friendly in a European context. This investment would probably be purely on commercial grounds. The establishment of a wider value chain in which the metals used in the production are also of Swedish origin poses a bigger challenge, and state involvement is pivotal to its growth. State involvement should primarily aim to manage and reduce risk. Several key risks are general to the mining industry and are discussed in Chapter 9. There are, however, specific initiatives that might be justified if a value chain from the extraction of graphite, lithium, and cobalt through to battery manufacturing were to be developed in Sweden.

6.4.1 Technological risk – familiar technology but a lack of expertise

The expertise needed to upgrade graphite, lithium, and cobalt production to the level that enables their use in batteries is not fully developed in Sweden. However, this knowledge does exist internationally. State support for research, pilot facilities, and test beds might help to attract this knowledge and further its development in Sweden.[33] The mining research facility planned for Pajala could be part of this, but this facility would require initial financial support and all relevant permits before it could operate commercially.

With regard to research, this could be developed as part of a programme for the entire value chain from exploration through to the manufacture of lithium-ion batteries. Such a programme would involve fields for which SGU, the Swedish Energy Agency, and Vinnova are responsible.

[33] See Hellsmark et al. (2016) for an analysis of the importance of pilot and testing facilities for innovation.

6.4.2 Market risk – spread the risk between players

Market risk is quite high for the manufacture of lithium-ion batteries and for value chains involving the extraction of graphite, lithium, and cobalt. This risk could therefore be shared between all the players involved to encourage each one to take the plunge. Successful clusters such as Silicon Valley and the Swedish iron and steel cluster have emerged from common commercial interests within the industry. The momentum of commercial interests develops and maintains these clusters over time, enabling them to grow into strong entities. In contrast, networking meetings organised and run by public institutions often lack a natural commercial driver, and such networks tend not to survive over time.

The development of a battery manufacturing cluster in Sweden should therefore be based on the commercial interests of the players involved. The state can support this development for a limited time by providing financial assistance to industry players in the battery manufacture value chain as they develop network partnerships. By way of example, the German government supports a battery forum that brings together leading actors in all steps of the value chain.[34] Because the value chain for battery manufacture is international and one purpose of such clusters is to attract leading expertise, networking activities should be in English.

6.4.3 Institutional risk – state priorities

The development of a value chain for battery manufacturing in Sweden is taking place in a rapidly expanding market where there is still the potential for establishing a hub for expertise and resources in Europe. In order to avoid any political risks, the government might need to communicate the importance of this development for Sweden. This could take the form of developing a strategy taking inspiration from the German strategy for battery manufacturing produced within the framework of the National Platform for Electric Mobility (NPE).[35]

The overarching national strategy for electric mobility was formulated in 2011 through co-operative work among the German federal government, industry, and trade unions. The objective is for Germany to become the leading supplier of electric mobility by 2020. The strategy covers the entire value chain from batteries and electric cars to online services for electric mobility. The political measures are a mixture of:

- direct financial support in the form of subsidies, tax relief, and public procurement
- support programmes that promote research and innovation
- the revision of legislation

The measures are targeted at different stages of the development of the value chain, their purpose being to make it market-oriented, that is to say, that the value chain should be economically viable without state support. The strategy has a large budget. As of 2016 the environmental bonus for battery-powered electric cars and plug-in hybrids amounts to

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[34] http://www.batterieforum-deutschland.de/infoportal/

[35] NPE (2017). Roadmap integrierte Zell- und Batterieproduktion Deutschland.[36] The REMinE project – Improve Resource Efficiency and Minimize Environmental Footprint – is part of the European network ERA-MIN, in which Luleå University of Technology is the Swedish participant. The aim of the project is to examine Yxsjöberg’s mining waste to assess the potential for extracting metals and minerals from the waste, as well as to study whether extracting metals from old mining waste is better than the post-processing of decommissioned mining areas. The project is also supported by Vinnova and AB Yxsjö Gruvor in their capacity as owners of the land of the old mining area.

EUR 1.2 billion, and from 2017 to 2020 EUR 360 million will be set aside every year for research and development.

7 Tungsten is needed in the steel and hard metal industry

Tungsten is an element that is firmly entrenched in the Swedish steel industry thanks to its specialisation in stainless steel, tool steel, and high-strength steel. Because of Sweden's robust steel industry, the need, and thus the economic importance, of tungsten is slightly greater for Sweden than for the rest of the EU, which means that it is categorised as slightly more critical from a Swedish perspective than a European one.

Tungsten does not occur naturally in pure form. The most economically important tungsten minerals are scheelite and wolframite. In Sweden, scheelite is mined in Yxsjöberg, for example, and this mine is currently included in an EU project examining the methods of extracting metals from old mining waste.[36]

In 2013, the global production of tungsten amounted to 71,000 tonnes.[37] China dominates with 80 per cent of global production. Austria comes fifth with 800 tonnes and a reserve of 10,000 tonnes. Sandvik owns the Felbertal mine in Austria, which ensures the reliable and cost-efficient availability of tungsten for Sandvik's steel production works.

7.1 Tungsten in environmental and technological innovations

Tungsten is a dense metal and has a very high melting point. Approximately 90 per cent of global tungsten production is used to produce ferro tungsten and hard metals based on tungsten carbides. The production of hard metals is completely dependent on the availability of tungsten and cobalt. Hard metal is a key component in many sectors of the European manufacturing industry. Hard metals are generally used by all engineering industries for the processing of other metals and minerals.

Tungsten is also used as an alloying element in steel, super alloys, and tungsten alloys. Tungsten alloys are used in a wide range of applications, including lighting, electronics, high-temperature technologies, welding, electro-discharge machining, aviation, spacecraft, weapons, and laser technology. Due to its high density, tungsten is also used in compensating weights and for radiation shielding, and it could therefore be used as a lead substitute. Although its density and subsequent shielding effect are much higher than for lead, it is used to a lesser extent for this purpose on account of its cost and the fact that it is more difficult to process.

7.2 Swedish strongholds in Tungsten

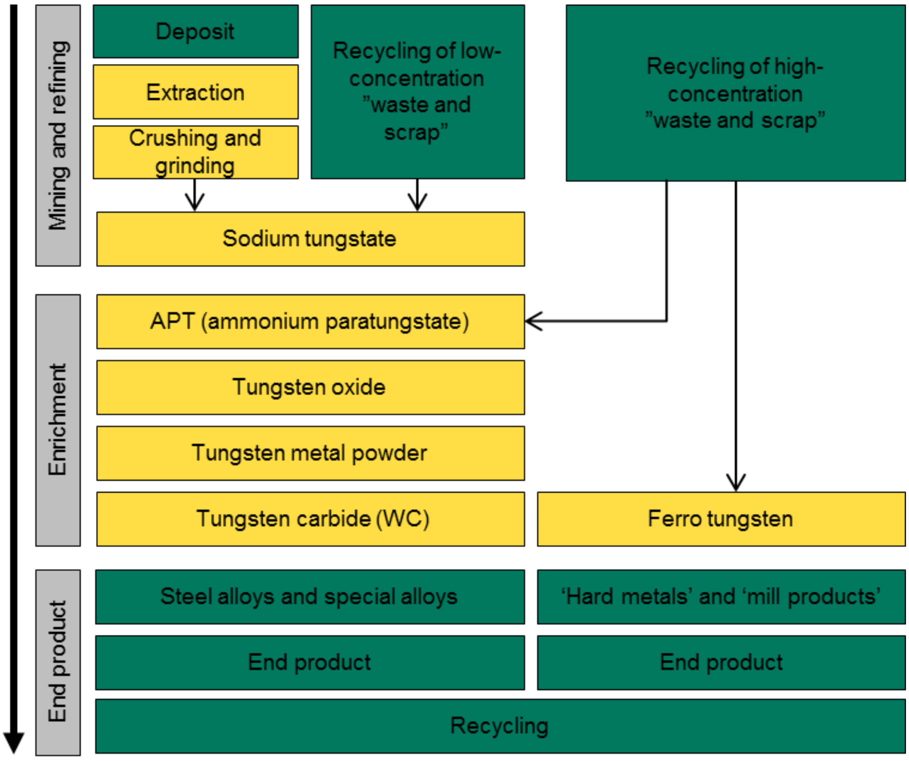
Sweden has relatively good geological conditions for the extraction of tungsten, with several lesser-known deposits. However, Sweden's strength currently lies in its high level of expertise in the upper levels of the value chain, especially the refinement of tungsten products primarily for the production of steel and hard metals. Sandvik and Höganäs in particular are two major players in this area.

[36] The REMinE project – Improve Resource Efficiency and Minimize Environmental Footprint – is part of the European network ERA-MIN, in which Luleå University of Technology is the Swedish participant. The aim of the project is to examine Yxsjöberg's mining waste to assess the potential for extracting metals and minerals from the waste, as well as to study whether extracting metals from old mining waste is better than the post-processing of decommissioned mining areas. The project is also supported by Vinnova and AB Yxsjö Gruvor in their capacity as owners of the land of the old mining area.

[37] https://minerals.usgs.gov/minerals/pubs/commodity/tungsten/mcs-2014-tungs.pdf

Figure 12 shows a potential value chain for tungsten. Just as for rare earth elements, the first refinement usually takes place close to the mine to keep transport costs down. However, enrichment usually takes place elsewhere, where recovered tungsten can be included in the process.

Figure 12 Value chain for tungsten



Source: Growth Analysis 2017. Green means that the conditions are good in Sweden compared with other countries. Yellow means there are other countries that currently have better conditions.

Sweden could strengthen its role in the value chain by exploiting its domestic deposits. Sweden is already good at recycling and refining tungsten, and domestic production would reduce Sweden's dependence on imports. Currently, only Sandvik has secured the availability of the raw material by integrating its tungsten mine in Austria into its production chain.

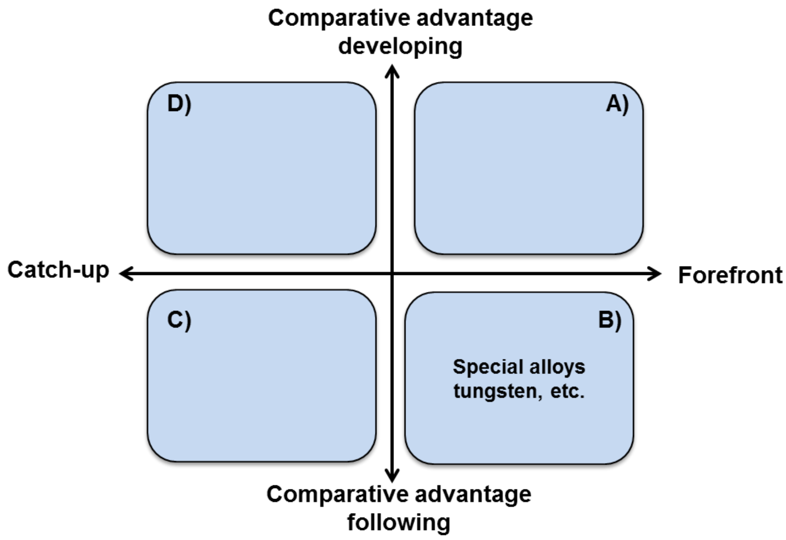
7.3 The role of the state relating to tungsten

According to the figure presented in Chapter 3, the Swedish special alloys industry belongs to the international technological front-line category. Special alloys are not, however, a rapidly expanding area (Figure 13). Rather, technological innovation focuses more on maintaining competitiveness against alternative materials. Research and the development of knowledge of special alloys is a Swedish position of strength that is supported by the state, and one that the state should continue to support through research funding according to the needs of the industry.

7.3.1 Market risk – reliable access

Any interest in the extraction of tungsten in Sweden should primarily be motivated by a company further down the value chain wanting to ensure access to tungsten. This means that extraction could take place on commercial grounds, though perhaps at a price that exceeds the global market price for tungsten. A competitive Swedish mine for tungsten could form part of this. Consequently, it is difficult to justify state measures directly targeted at tungsten apart from initiatives related to mining in general, and measures that aim to support mining and recycling from mining waste and consumer products more generally would be key to creating the conditions for tungsten in Sweden.

Figure 13 Innovation position for tungsten in special alloys in Sweden



8 Recycling from mining waste and consumer products

Recycling critical metals and minerals from mining waste and consumer products is an area of growing importance. Within the EU, where most Member States lack access to domestic mines, this is reflected in strategies that promote a circular economy. This focus is likely to continue. Present knowledge of metals and minerals in Sweden can be of value in this development, while recycling critical metals could complement and possibly even be an alternative to primary mining. Recycling should therefore be an integrated element of a minerals strategy. This chapter summarises some of the major challenges Sweden faces in this area.

8.1 Recycling from mining waste

Residual material from mining operations is generated in the extraction of ore and in the subsequent enrichment of the ore into a metal concentrate. In addition, residual material is generated during smelting and in blast furnaces. Mines are very waste-intensive, and the quantity of mining waste produced annually in Sweden is much greater than for all other types of waste combined.[38]

Because a mining concession is often limited to one or a few individual materials, other metals and minerals might remain in the mining waste. There are two main reasons why it could be interesting to attempt to recover residual material from old mining operations. Firstly, modern enrichment methods make it technically viable to extract these materials where previously this was impossible. Secondly, the price of metals and minerals might justify the costs of extracting residual material.

A fundamental difficulty of using mining waste as a resource is that it is legally classified as waste and not as a potential resource. This results in several uncertainties. One of these is the unclear distribution of responsibilities within and between authorities. Waste issues are the responsibility of the Swedish Environmental Protection Agency, while responsibility for the extraction of metals and minerals lies with the SGU. The end result is that mining waste is not treated as mining pursuant to the Swedish Act on Mining (SFS 1991:45). A process in which waste is recycled is subject to reporting and licensing pursuant to Section 29 of the Swedish Regulations on Environmental Testing (2013:251). Thus recovering waste involves waste being reclassified from waste to an object or substance that is covered by other legislation. Johansson et al. (2017) state that the institutional division between the Swedish Environmental Protection Agency and the SGU means that there is no consensus on waste as a resource and as an environmental problem. Complete consensus on this matter has not yet been reached in relation to efforts on the strategy for the sustainable management of mining waste that the Swedish Environmental Protection Agency and SGU developed on behalf of the Swedish government in 2017.[39] Mining waste is exempt from landfill tax, which is justified in SOU 2005:64 by the fact that taxing such large quantities of waste would be difficult for the mining industry to bear.

[38] Swedish Environmental Protection Agency (2016).
[39] http://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/regeringsuppdrag/2017/gruvavfall/strategi-forslag-hantering-gruvavfall-20170913.pdf[40] Swedish National Institute of Economic Research (2016).

Furthermore, mining waste can be considered as inevitable given the production process, and it can be difficult to reduce the quantities of waste generated.

The tax exemption reduces the incentives for reducing waste. If the aim is management according to a waste hierarchy, a landfill tax would increase the incentives for reusing or recycling gangue and other inert material. This would mean a levelling of the competition between the extraction of virgin minerals, which is exempt from landfill tax, and extraction from decommissioned waste facilities, which is subject to a landfill tax on residual waste.[40]

8.2 Recycling from consumer products

Increased recycling provides an opportunity to reduce dependence on imports of innovation-critical minerals and metals. The proportion of recycled innovation-critical minerals and metals is generally low, often less than one per cent. The reasons for this are that innovation-critical metals and minerals occur in low concentrations in complex products, there is insufficient information regarding the content of waste, and recycling technology is not yet fully developed.

There are several obstacles to achieving an optimal level of recycling from products. These relate not only to the full integration of the environmental cost in the materials cycle, but also to other obstacles. These include asymmetrical information, a lack of information, and technical externalities.[41] These are described in the form of risks in this section.

8.2.1 Technological risk

Innovation-critical minerals and metals generally occur in low concentrations. This makes high-quality recycling both time-consuming and technically challenging. A growing challenge is that products are not designed for recycling. An illustration of this is mobile phones, where it is becoming increasingly difficult to access the battery. In the future, it is expected that it will become even more difficult to recycle innovation-critical minerals and metals. The reasons include:

- The need to develop products with better performance and new features without increasing their size or weight. This results in smaller components containing innovation-critical minerals and metals, more compact packaging, and a broader mix of materials.
- Rapid product innovation and thus the reduced lifespan of products means constant changes for the recycling industry to adapt to.[42]

There are currently no strong incentives for producers of consumer products to adapt their designs to simplify recycling. Product design is instead adapted to performance requirements, increased cost effectiveness, and other customer requirements. There are exceptions to the above, however. One example is the recycling of platinum from vehicles' catalytic converters.

Because developing cost-effective recycling technologies for innovation-critical minerals and metals is a challenge due to the wide variety of material compositions and their low concentrations, the development and commercialisation of recycling technologies has been limited to those metals that are the most economically profitable to recycle. This primarily

[40] Swedish National Institute of Economic Research (2016).
[41] Nicolli et al. (2012).
[42] Bacher et al. (2016).

relates to gold and copper in electronics. That said, Boliden Rönnskär recycles several metals – palladium, platinum, gold, and silver – from electronic waste. Aluminium and iron are often recycled as well.

8.2.2 Market risk

Prices vary due to variations in the quantity and quality of recovered innovation-critical minerals and metals.[43] This makes it difficult for a potential investor to estimate profitability. This is exacerbated in that the recycling industry struggles to guarantee quantities and quality, which creates distrust among customers when confidence in the industry is already low due to a lack of third-party checks on the quality of the recycled material. The cost of landfill waste is often not high enough to justify recycling, and some of the material ends up in the economically lucrative waste-incineration industry. All in all, recycling innovation-critical minerals and metals is often less profitable.

8.2.3 Institutional risk

Recycling is hampered by the lack of harmonisation in EU regulations and by Member States' varying implementation of these regulations. The differences in implementation mean that recycling players need to keep track of the legislation in several countries, and it is difficult to obtain reliable data for evaluating the potential for recycling different materials. There is no official source that collects data on the availability of innovation-critical minerals and metals in different products or how much is imported or exported in the products.

Within the EU, estimates of recycling levels are based on mass. This creates no incentives for recycling innovation-critical minerals and metals because the concentrations of these in products are generally low. For instance, Directive 2000/53/EC on end-of-life vehicles has the objective of reusing or recycling 85 per cent of all vehicles by 1 January 2015, and Sweden has fluctuated around this figure since 2009. Despite this high recycling level, innovation-critical minerals and metals from vehicles are rarely recycled because these are generally found in small quantities and spread across the entire vehicle.[44]

[43] van Eersel (2016).
[44] Andersson et al. (2016).

9 Policy discussion

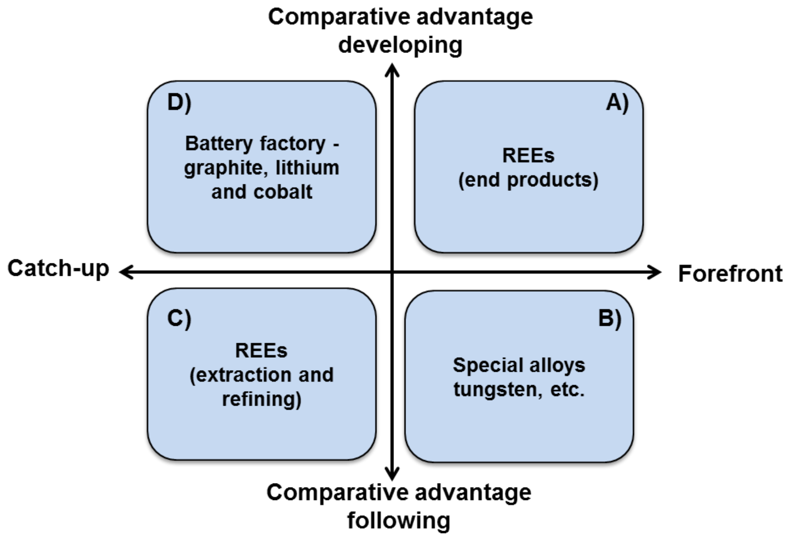
This chapter is based on the assumption of the state wanting to establish various measures to enhance the development of a cluster for innovation-critical metals and minerals in Sweden.

The value chains we have analysed each come with different challenges. Graphite, lithium, and cobalt used in the manufacture of batteries are characterised by high risk with a market that is developing rapidly (see Figure 14 and Chapter 6). At the same time, Sweden has limited expertise within key elements of the value chain for these materials. Sweden's big competitive advantage for battery manufacture is the availability of cheap and green electricity. Another competitive advantage might be the extraction and refinement of graphite, lithium, or cobalt. This would create the conditions for the better utilisation of core expertise as well as guaranteed prices and access to critical metals. Although Asia is well ahead in terms of the production of battery cells, Sweden has its own strengths in the form of the battery research group in Uppsala, which could be developed further.

Sweden is a leader in the development of special alloys. Innovations in this area will, however, pertain primarily to maintaining competition in existing markets (see Figure 14). In recent years the vertically integrated ownership of mines has become a strategy to ensure the availability of metals as well as to possibly keep down the cost of producing special alloys. This is a strategy that is also used to lower the production cost of batteries.

Identifying Sweden's position in a value chain for rare earth elements is more difficult. Rare earth elements occur in many products, not least in communication technology, which is used in rapidly developing markets and is a field in which Sweden, in various aspects, is at the technological front line. Segments such as permanent magnets, which contain rare earth elements, are, however, quite established markets lacking in Swedish players. China is at the forefront of developing increasingly optimised value chains for rare earth elements. So far, Sweden and Europe are strongest in the later stages of the value chain, such as end products and recycling. That said, China's ambitions threaten even Sweden's position at the technological front line. A Swedish or European value chain faces a major challenge when it comes to being and remaining competitive.

Figure 14 Innovation position for Swedish value chains



Because the value chains face different challenges, innovation policy needs to be formulated differently. The reason for this is that the risks that need to be managed vary between value chains. Value-chain-specific initiatives are described in Chapters 5, 6, and 7. However, the overall innovation capacity needs to be strengthened regardless of the value chain (see Table 3).

Table 3 Innovation policy for value chains relating to critical metals and minerals

Policy orientation	**Key needs**	**Policy instruments**
Develop general innovation capacity	- Develop the ability to acquire knowledge - Incentivise companies to innovate	- Stimulate the exploration of innovation-critical metals - Support knowledge-building, not least about the Swedish bedrock - International knowledge-sharing and networking - Improve business opportunities and public attitudes towards mining - Improve infrastructure - Improve regulation - Taxes and general market instruments
Support innovation at the forefront and new markets	- Solve technical barriers - Develop radical innovations - Weaken existing conflicting interests - Solve societal challenges without commercial interests	- RD&D support, particularly thematic and towards societal challenges - International cooperation - Technology-specific demand management - Regulatory reforms - New business models - Networking
Develop strongholds and catch up with or develop competitiveness	- Support incremental changes - Increase efficiency - Stimulate access and use of innovative technologies	- Custom RD&D support based on companies' needs - Tax incentives for increased commercial innovation - Taxes and general market instruments - International co-operation - International trade and trade agreements - International researcher exchange

Source: Inspired by Dutz and Pilat (2012) and Dutz and Sharma (2012)

9.1 Initiatives to strengthen overall innovation capacity

Initiatives to strengthen overall innovation capacity aim to mitigate the technological, market, and institutional risks of mining in Sweden.

9.1.1 Market risk

The market risk of mining and recycling innovation-critical metals and minerals is significant. Profitability is difficult to estimate, and this is why the ability to identify the most suitable deposit and recycling potential is important. A prerequisite for this is improving knowledge of the Swedish bedrock and its conditions. This covers everything from improving basic knowledge to more exploration in order to identify local availability of critical metals and minerals in Sweden. State support for basic knowledge of Swedish mineralogy currently comes almost exclusively from SGU's research support. They have a research budget of SEK 6 million per year, which is probably insufficient. Knowledge of and data on geological potential needs to be made readily available. Sweden used to be at the forefront of data access but has been overtaken by other countries in recent years. Consequently, measures might be needed to improve data access by offering harmonised, easily accessible two- and three-dimensional digital geological data.

Sweden has the potential to sell metals and minerals that are sustainably produced, and this could be a general advantage for the Swedish mining industry. Transparent and credible systems that enable aspects of sustainability to be taken into account might facilitate the consideration of this value.

Labelling metals and minerals

The sustainability labelling of metals and minerals can be facilitated by taking both environmental and social sustainability into account. Metals and minerals are currently not labelled, meaning that even if customers were willing to pay a premium for sustainable products, this is not realised. Examples of sectors where such a transition has occurred include organic foods and eco-labelled wood.

Creating demand for sustainable metals and minerals in products

Instruments that create demand for sustainably produced products can be used at least initially to create a niche market. Products containing sustainable metals and minerals are usually likely to be more expensive to produce than traditional products. It is uncertain whether consumers would be willing to pay this extra cost, even if it was very small in relation to the overall cost of the product. Although consumers with a willingness to pay exist, they might be too few to be economically viable. This means that there is a risk associated with the transition to sustainable products. In order to get through the initial transition and to establish a market, there might be a need for some form of financial support or guarantee that ensures profitability for the first industries in the transition.

In addition, a lot of energy and environmental legislation currently centres on reducing energy consumption or emissions from the operation of vehicles and products. A consequence of this approach is the risk that emissions and energy use increase in other parts of the value chain. For instance, vehicle greenhouse gas emission requirements result in vehicle manufacturers switching to batteries and using more lightweight materials. Although both of these strategies result in lower emissions from vehicle use, there are greater emissions resulting from their production. By way of example, a Tesla car needs to be driven for around eight years before its emissions from a life-cycle perspective fall below a comparable petrol or diesel-powered vehicle.[45] This sub-optimisation can be avoided by using instruments that take into account greenhouse gas emissions from a life-cycle perspective.

9.1.2 Institutional risk

The institutional risk for mining is perceived to be increasing in Sweden (see Chapter 4.3.2). This is due not least to the vast land requirements for mining that extend over long periods of time and affect other social interests.

Transparent, clear, and credible processes and criteria for weighing interests against each other

It is difficult to weigh land interests against each other, and there are weaknesses in the current process. Firstly, the purpose of the mandatory requirements to assess an application's impact on the environment and cultural heritage is to assess the *negative* impact of a mine. However, there are no requirements or tools for how to weigh the *benefits* of a mine. In other countries, the application requests a description of the benefits to the local community and other stakeholders. This is essential for being able to balance the negative impact of mining against its benefits. The permitting procedure should therefore include a binding plan for how the company will ensure that the benefits are realised. This could include partnerships with companies, towns and cities, and other stakeholders.

The risk of not taking the benefit perspective into account in the assessment has increased in that matters related to enterprise and innovation have moved from some county administrative boards to the regional level. This means that the county administrative boards in these areas might be expected to show less regard for business interests in their considerations.

Secondly, it is difficult to weigh different land use interests against each other. For instance, how should 'hard values' such as tax revenue and jobs be weighed against a certain way of life? This is exacerbated by the need to weigh future benefits and impacts against current conditions. In reality, this sort of comparison is very difficult to carry out. The EU project STRADA (Strategic Dialogue on Sustainable Raw Materials for Europe), financed within the framework of Horizon 2020, addresses the issue of long-term reliability of supply in relation to the sustainability of the supply of European raw materials from European and non-European countries.

The system of Swedish national interests is one way the state can weigh the different interests against each other. That said, in this system all the interests are equal, except for defence interests, which are paramount. However, the system of national interests lacks a formal tool for evaluating the benefits of different land uses. Consequently it risks being preservative. For an applicant, the absence of clarity, transparency, and tools for evaluating the various interests poses an uncertainty, which subsequently poses an institutional risk.

Knowledge of the different land interests and how they conflict with one another could also be improved. Shared knowledge activities carried out by the authorities with various stakeholders such as the SGU and the Swedish Environmental Protection Agency could contribute to the establishment of better understandings between stakeholders. The Swedish Agency for Marine and Water Management's partnership with the Swedish

[45] IVL, 2017.

Energy Agency regarding hydroelectric power can serve as inspiration for such activities. The purpose of these dialogue efforts was to create shared knowledge in order to balance energy and environmental values.

EU processes also lack a benefits perspective. Raw materials and the health risks they pose for anyone handling them during their extraction and the onward refinement process are regulated by way of various European safety regulations, primarily REACH, which came into effect in 2007. The greater responsibility for assessing and managing the risks of chemicals (substances) such as cobalt has shifted from the authorities to the industry by way of registration and self-classification under the REACH agreement. In the case of cobalt, however, the Netherlands has submitted a proposal to the European Chemicals Agency (ECHA) regarding stricter limits. The proposal for the harmonised classification of metallic cobalt differs considerably from the classification set by the industry. The proposal would have far-reaching consequences for the use of cobalt in products such as stainless steel, hard metal, and lithium-ion batteries. The classification as carcinogenic, mutagenic, and/or toxic for reproduction might lead to further action at the European level, such as through the need to obtain a licence before use. The proposal from the Netherlands is heavily influenced by results from various studies based on animal testing that varies in scope and quality and which is not supported by new epidemiological studies.[46]

Clearer requirements in permitting

In interviews for this project, it emerged that new mining players in Sweden struggle to understand what a full application for a mining concession should contain. The result is often that the application is unnecessarily sent back and forth many times between the applicant and the permitting authority. There are also calls for the permitting process to have a more predictable schedule. This is especially important for mining companies financed with venture capital because this affects the possibility of obtaining capital and the cost of this capital. A mining project does not generate revenues until mining starts. Prior to this, there are only expenses.

Mining companies can help decision-makers

In the early 1990s, Canadian mining companies came under heavy fire after deficiencies in their operations were brought to light. In order to improve their reputation, the mining companies developed their operations and improved their risk management. In 2004 these efforts resulted in the Towards Sustainable Mining (TSM) initiative.[47] To be part of TSM, mining companies have to meet a number of environmental and social requirements, as well as regularly report any deviations from these requirements publicly. The requirements are often stricter than the minimum legal requirements.

The Finnish mining industry later introduced a similar system. Experience has shown that the public perception of the Finnish and Canadian mining industries has become more positive since the introduction of these initiatives.

9.1.3 Technological risk

A general challenge for the mining industry is ensuring the availability of expertise, not least in light of a deluge of retirement departures. Specific initiatives will be needed to ensure the availability of labour. This challenge is particularly relevant to the availability

[46] Sauni et al. 2017; Marsh et al. 2017.
[47] The Mining Association of Canada, 2017: Towards Sustainable Mining 101: A Primer.

of labour with extensive knowledge of Sweden's mineralogy. This is an area that has long been neglected despite knowledge being key to an attractive mining industry. SGU has a research budget of approximately SEK 6 million that must be spread across a wide area. Vinnova does not fund basic research; it only funds innovation projects, including projects in the field of mining. One question that should be asked is whether it is appropriate to split up research efforts across several authorities. However, this question was not analysed in this project.

EU programmes are an important source of funding to ensure maximum effect. One example of this is the recently established European Innovation Partnership on Raw Materials, which is the EU's largest innovation venture in the raw materials sector.[48] Sweden already has a number of initiatives with long-term effects in research and innovation in the mining sector, such as SIP STRIM, which is co-financed by Vinnova, Formas, and the Swedish Energy Agency.[49] The SIO Graphene programme, which is based on the EU's Graphene Flagship initiative, is another example of an ongoing programme where current basic research can put Sweden in a favourable position for the future because Chalmers both co-ordinates and leads the European project and the SIO programme.[50]

[48] https://eitrawmaterials.eu/
[49] SIP STRIM (2017)
[50] SIO Graphene (2017)

10 Conclusions

The project described in this report involved two primary tasks: (i) mapping the need for innovation-critical metals and minerals, and (ii) analysing and providing information regarding what might be required in order for the *entire production chain – from extraction to finished product* – of the identified environmental and technological innovations to be located in Sweden.

10.1 The need for innovation-critical metals and minerals

Demand for innovation-critical metals and minerals are growing rapidly. Demand is driven by the development of permanent magnets, batteries, special alloys, fuel cells, and solar cells. Permanent magnets have a special status in this context because they are a fundamental technology in an electrified society. This means that modern technology is particularly dependent on the availability of rare earth elements, and a society with electrified vehicles powered by renewable electricity is an impossibility without access to rare earth elements.

Several innovation-critical metals and minerals might be extracted in Sweden. This is not least the case for rare earth elements and graphite. In addition, there is potential for the extraction of lithium, nickel, and tungsten, and to a certain extent also cobalt. This means that Sweden has an interesting geological potential with regard to the rapidly growing demand for lithium-ion batteries, permanent magnets for electronics, and many special alloys within the steel industry. This geological potential exists not only in new mines, but also in mining waste.

The potential for extracting several innovation-critical metals and minerals such as gallium, germanium, chromium, manganese, and platinum is, however, small. These innovation-critical metals and minerals are common in solar cells and fuel cells.

In general, the recycling of innovation-critical metals and minerals from consumer products is low. Even if this was technically possible, it would not be profitable because there are only small quantities contained in these products, which are developing rapidly both in terms of their design and choice of materials.

10.2 Development of value chains

The aim of this project was to analyse and provide a basis for measures that might result in entire value chains being located in Sweden. However, this starting point is not appropriate for a small market-oriented nation like Sweden. The starting point should instead be identifying where Sweden might have comparative advantages and how these can be developed. For instance, Sweden is a world-leading producer of certain high-quality steels from iron ore. Almost all of this steel is exported, however, before it finds its way into consumer products. Pushing the extraction of innovation-critical metals and minerals in Sweden could result in higher costs for consumers of these resources in the value chain and thus weaken competitiveness. At the same time, the extraction of innovation-critical metals and minerals in Sweden might result in better reliability of supply and increased access to expertise. This project did not include an analysis of whether the state should have specific initiatives targeting value chains based on innovation-critical metals and minerals, and the main purpose of this analysis was to identify measures that the state can implement to support innovation.

In our analysis, we have identified comparative advantages and weaknesses within three value chains – rare earth elements, lithium-ion batteries, and special alloys containing tungsten. Because Sweden's geological potential is good or very good for all three of these value chains, measures that facilitate mining in general are key to the development of these value chains.

In the case of rare earth elements and special alloys containing tungsten, the assessment is that Sweden should not introduce measures beyond those that support mining in general. Rather, rare earth elements should be seen from a European perspective because a European value chain would likely be more feasible. We feel, however, that a European value chain would be difficult to commercialise because of competition with existing Chinese clusters on commercial grounds. Consequently, there is significant market risk, and given that reliability of supply is viewed as a necessity, the state needs to implement measures to mitigate this.

The state could bolster the development of a value chain for lithium-ion batteries, and there are possible spillover effects in the development of this value chain. Swedish battery manufacturing could create an incentive for the extraction of graphite, lithium, and cobalt and could be integrated vertically within battery manufacturing, which would potentially lead to lower production costs.

10.3 Recommendations

Sweden has the potential to extract several metals and minerals that are critical for environmental and technological innovations. In light of growing international demand for these metals and minerals, interest in their extraction is likely to increase. That said, there are market imperfections that risk damping the interest in their extraction in Sweden, despite it being generally more environmentally friendly to do so here than in other countries. With regard to the extraction of critical metals and minerals, the following market failures are cited with proposals for remediation.

Include benefits in licensing processes

The application for a mining concession includes requirements for assessing the impact on the environment and cultural heritage. However, the process has no requirements or tools for how to take the benefits of a mine into account. Consequently, the application should also require a description of the benefit to the local community and other stakeholders, as well as a description of measures that would result in the realisation of these benefits to society.

The spirit of the legislation should be:

The purpose of a socio-economic impact assessment for an enterprise or measure is to identify and describe the direct and indirect economic impact that the planned enterprise or measure might have on society and the population, both in the local area and at the regional, national, and international level. Furthermore, the aim is to enable an overall assessment of whether these effects have been realised.

The socio-economic impact assessment should be supplemented by a plan for the realisation of the socio-economic values that will arise as a direct result of the enterprise. In its plan, the enterprise should state how it will work to achieve the socio-economic benefits described in the socio-economic impact assessment.

In addition, the benefit of metals and minerals for value chains needs to be taken into account in the development of EU regulations, such as in the development of REACH and the Eco-design directive. Ignoring this benefit during the shaping of requirements poses a threat to much of the European engineering and manufacturing industry.

Credible labelling is needed to bring about a willingness to pay

There is a willingness to pay for more sustainably produced consumer products. A prerequisite for bringing about this willingness to pay is a credible system that ensures that the consumer will get what he or she is paying for. The sustainability labelling of metals and minerals would most likely benefit the Swedish mining and recycling industry, which by international standards is environmentally sustainable.

There are benefits to the state developing a system for the sustainability labelling of metals and minerals. First and foremost, state regulation can set requirements regarding verifiability and transparency. However, it might be more effective if the industry itself developed a system for sustainability labelling. Such a system could be created within a value chain, for example, from extraction to more sustainably produced lithium-ion batteries. However, it is more difficult to envisage a value chain that features sustainability labelling that extends all the way to a finished vehicle. A vehicle is made up of thousands of components and many metals of various different origins. It would take some time before all of these components could be part of a sustainability labelling system.

An analysis is needed of the pros and cons of various systems for the sustainability labelling of metals and minerals. In this context, these advantages and disadvantages relate to the creation of an understanding of the potential to create sustainable value chains by means of labelling. This involves analysing how competitiveness is affected as well as by clarifying how the state can stimulate demand for products containing sustainably produced metals and minerals.

Ensure expertise

A prerequisite for sustainable mining activities is access to expertise for companies, authorities, and courts. However, Sweden's mining industry faces a skills drain due to retirement departures and a lack of trained students with sound expertise in Sweden's specific geological conditions who can replace those who retire. Consequently, more funding is needed for basic and applied research that also aims to enhance and ensure long-term expertise in Swedish geology.

There is currently a conflict between anti-mining interests and business interests that centres around mining activities. In recent years this conflict has become more politically charged, and dialogue based on knowledge is needed in order to find a middle ground in this conflict. Consequently the SGU and the Swedish Environmental Protection Agency should be tasked with arranging dialogue sessions with relevant parties and with producing information for guidelines on how mining and environmental interests should be evaluated. Dialogue sessions on hydropower and the environmental value of waterways arranged by the Swedish Energy Agency and the Swedish Agency for Marine and Water Management can be used as inspiration.

Special support for the extraction and refinement of graphite, lithium, and cobalt

Specific initiatives might be important for the development of a value chain for the extraction of graphite, lithium, and cobalt for battery manufacture:

- Indicate the political priority and target financial support at the value chain. Initiatives might be needed to demonstrate the political desire for the development of lithium-ion batteries and a cluster surrounding this. Part of this is focused on financial research initiatives.
- Support pilot and testing facilities. The state might have to support the development of pilot and testing facilities. This could relate to the processing and upgrading of graphite, lithium, and cobalt to a level that enables their use in batteries.
- Create conditions for labelling that reflect the sustainability of the production of lithium-ion batteries, and work to ensure that this becomes an international standard that is included in EU legislation.
- Support the establishment of open clusters and networks operated by commercial interests. The state can support this development for a limited time by providing financial assistance to industry players in the battery manufacturing value chain as they develop network partnerships. Because the value chain for battery manufacturing is international and one purpose of such clusters is to attract leading expertise, networking activities should be in English.

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Appendix

Appendix 1 – Rare earth metals and their usages

Rare earth metals refer to the 15 elements contained in the lanthanoid group: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Scandium and yttrium are also often included due to their similar properties to many elements of the lanthanoid group. Frequently, analyses such as the EU's work on critical raw materials differentiate between "light" and "heavy" rare earth metals based on their different chemical properties, geological availability, and respective market values and end-markets. Scandium is not considered a critical raw material.

Appendix Table 1 shows the average availability of rare earth metals based on information from 51 deposits. The light rare earth elements often exist in larger concentrations, while the heavy rare earth elements are rarer and thus often exist in smaller concentrations. The Swedish deposit in Norra Kärr contains a large share of the heavy rare earth metals.

Appendix Table 1 Rare earth elements and examples of their usage

Name	***Chemical symbol***	***Natural occurrence***[51]	***Example of usage***
Light rare earth metals (LREE)			
Lanthanum	*La*	*24.9%*	*Petroleum refining (cracking), catalysts, battery electrodes, camera lenses, within the photo industry for studio and projection lighting*
Cerium	*Ce*	*43.2%*	*Catalysts, steel production*
Praseodymium	*Pr*	*4.6%*	*Permanent magnets, colouring agents in ice creams and ceramics, lasers*
Neodymium	*Nd*	*16.2%*	*Extremely strong permanent magnets, microphones, electronic engines for hybrid cars, lasers*
Promethium	*Pm*	*-*	
Samarium	*Sm*	*2.2%*	*Permanent magnets, cancer treatments, x-ray lasers*
Heavy rare earth metals (HREE)			
Europium	*Eu*	*0.3%*	*Colour TV screens, LED lamps, fluorescent glass, genetic screening*
Gadolinium	*Gd*	*1.4%*	*Magnetic cooling, metal production, increasing the quality of alloys*
Terbium	*Tb*	*0.2%*	*Additive in permanent magnets, TVs, fuel cells, naval sonars*
Dysprosium	*Dy*	*0.9%*	*Additive in permanent magnets, commercial lightning, hardware units*
Holmium	*Ho*	*0.2%*	*Lasers, glass colouring, high-strength magnets*
Erbium	*Er*	*0.5%*	*Signal reinforcement in fibre optic cables, laser glass, metallurgical usages*

[51] European Commission (2016) Report on Critical Raw materials for the EU. Critical raw material profiles.

Name	**Chemical symbol**	**Natural occurrence**[51]	**Example of usage**
Thulium	*Tm*	*0.1%*	*High performing lasers, portable x-ray machines, high temperature superconductors*
Ytterbium	*Yb*	*0.4%*	*Improvement of stainless steel, lasers*
Lutetium	*Lu*	*0.1%*	*LED lamps, integrated circuit manufacturing, medical isotope radiation therapy*
Scandium	*Sc*	*-*	*Space technology and avionics, special alloys, neutron generators*
Yttrium	*Y*	*4.9%*	*TV and computer screens, CFL and LED lamps, cancer treatments, special alloys*

Interviews

Growth Analysis interviewed representatives from the following agencies:

- The Mining Inspectorate
- Geological Survey of Sweden
- Swedish Environmental Protection Agency
- Swedish Environmental Research Institute (IVL)
- Luleå University of Technology
- Uppsala University
- BASF
- Northvolt
- Sandvik AB
- Talga Resources

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Growth Analysis is an analysis agency under the direction of the Ministry of Enterprise, Energy and Communications. We are commissioned by the Government to evaluate and analyse Swedish growth policy.

Our task is to strengthen Swedish competitiveness and create the conditions for more jobs in a larger number of growing companies throughout the country. We do this through providing the government with an advanced knowledge base and recommendations to develop, review and streamline its work to promote sustainable growth and business development.

Expert personnel, unique databases and developed collaboration at national and international level are important assets in our work. The Agency's primary target groups are the Government, the Swedish Parliament and other agencies within our field of knowledge. We take an independent position in our evaluations and analyses.

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