Environmental aspects related to the use of critical raw materials in priority sectors and value chains

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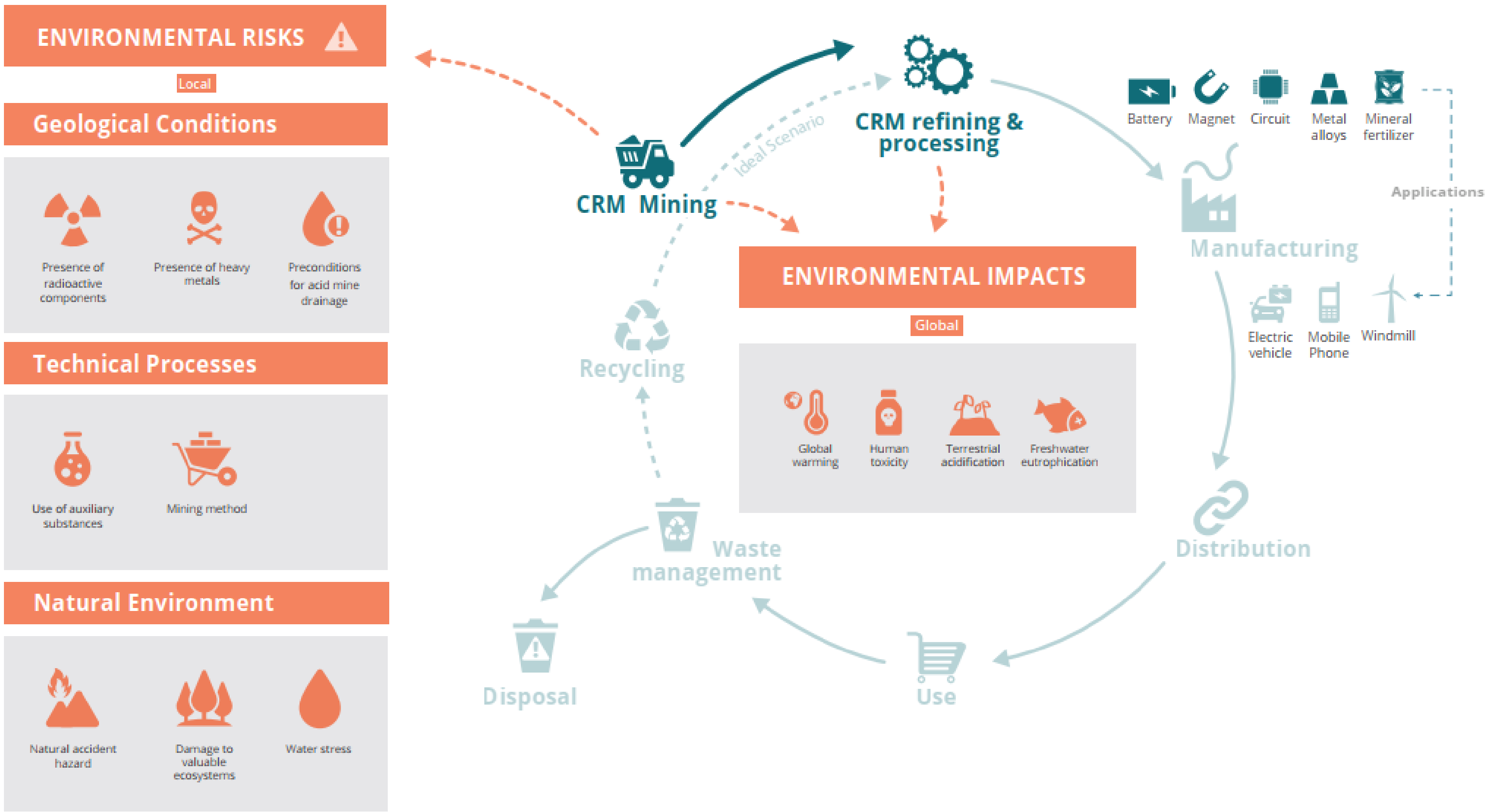

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Key messages

- Critical raw materials (CRMs) are important in many strategic industrial sectors such as clean technologies vital for ensuring a carbon neutral Europe and modern technologies crucial to the digitalisation of future industry/society. Often critical raw materials are used in different applications because they provide unique properties that are difficult to achieve otherwise; thus, in many cases, there are no viable substitutes for critical raw materials.
- Particularly high global environmental impacts can be observed for those critical raw materials that are essential for producing functional metal alloys and those that are needed for agricultural fertiliser production, due to the high production volumes of these applications. The magnitude of the individual impacts of a critical raw material in an application is the result of a combination of the environmental impact of producing of one tonne of the critical raw material on the one hand, and the number of tonnes of that critical raw material required for the global production of the particular application on the other.
- A fair comparison of environmental impacts of a critical raw material and its possible substitutes is challenging. As substitution of critical raw materials in many cases also changes the design of the component and the end product, it is important to take account of all changes that occur over the product's lifecycle, including its use and end-of-life management.
- Typically, the development of substitution solutions for critical raw materials is driven by performance and functionality, as well as the reduction of costs and supply risks, rather than environmental aspects. Nevertheless, better performance and functionality often result in reduced environmental impacts.
- For some critical raw materials, such as phosphorus used in mineral fertilisers, element to element substitution is not possible. Secondary raw materials could in this case support the supply, but recycling from post-consumer waste/scrap of many critical raw materials is currently negligible.
- In addition to the global environmental impacts, the mining of critical raw materials generates substantial environmental risks in the countries where extraction takes place, often countries with poor environmental legislation. These risks are related to the geological conditions at the extraction site, such as the presence of heavy metals in the ores; the mining and extraction technology which can lead to the destruction of ecosystems by an open-pit mining; and the natural conditions of the extraction site, for example if it is in a water-stressed region.
- Policy recommendations aimed at reducing the environmental risks associated with the extraction and processing of critical raw materials include the implementation of sustainable sourcing practices, and, for those critical raw materials and related substances that present risks such as (eco)toxicity and carcinogenicity, the monitoring of observance of strict national and international standards and regulations applicable to the production, use, transport, trade and disposal of hazardous substances.

1 Introduction

The products, devices and services we use and consume in today's society play a significant part in the quality of life. These products have evolved over the last decades with functions that improve our ways of life. In addition, services we use, for example to provide energy and electricity for our devices and living, are just as important. Many of these products and services are truly complex and require a great many different raw materials, some of which are especially important to the EU's economy yet their supply is far from secure. These raw materials are called critical raw materials (CRMs). The European Commission publishes a list of these, which is regularly reviewed and updated.

These critical raw materials often provide unique properties to materials and components which are used in various products, from mobile phones to electric vehicles and wind turbines. They have, for example, enabled the miniaturisation of components, wireless technology and mobility as well as various green technologies. In many cases substitution of these critical raw materials would lead to loss of performance in the applications. Thus, many technologies currently depend on critical raw materials and this will likely remain so in the near future.

Environmental impacts and risks related to critical raw materials are often a two-sided question since some of the products and technologies which utilise critical raw materials, such as wind turbines and solar panels, were partly developed to reduce environmental impacts, yet the mining and refining of critical raw materials have significant environmental consequences. In addition, substitution solutions are often driven by functionality and performance, with the environmental aspects remaining unclear.

This report describes the importance of critical raw materials, their substitution solutions and assesses the environmental aspects related to them and their possible substitution solutions. For the assessment, five key applications were selected through a screening process, namely: permanent magnets, batteries, alloys, mineral fertilisers and electronic components.

This assessment is based on the third list of critical raw materials published by the European Commission in 2017, the most recent information available during the preparation of this report. A new list of critical raw materials has been published in September 2020. Critical raw materials on the 2017 list stay on the 2020 list with the exception of helium, which is removed due to a decline in its economic importance. In addition, bauxite, lithium, strontium, and titanium are added to the 2020 list.

Critical raw materials, including different rare earth elements and platinum group metals, as well as their chemical symbols are listed in Table 1.1.

Table 1.1 Critical Raw Materials (2020 list)

Antimony	Sb
Baryte	
Bauxite	
Beryllium	Be
Bismuth	Bi
Borate	
Cerium*	Ce
Cobalt	Co
Coking coal	
Dysprosium*	Dy
Erbium*	Er

Europium*	Eu
Fluorspar	
Gadolinium*	Gd
Gallium	Ga
Germanium	Ge
Hafnium	Hf
Helium	He[1]
Holmium*	Ho
Indium	In
Iridium+	Ir
Lanthanum*	La
Lithium	Li
Lutetium*	Lu
Magnesium	Mg
Natural graphite	
Natural rubber	
Neodymium*	Nd
Niobium	Nb
Osmium+	O
Palladium+	Pd
Phosphate rock	
Phosphorus	P
Platinum+	Pt
Praseodymium*	Pr
Promethium*	Pm
Rhodium+	Rh
Ruthenium+	Ru
Samarium*	Sm
Scandium*	Sc
Silicon metal	Si
Strontium	Sr
Tantalum	Ta
Terbium*	Tb
Thulium*	Tm
Titanium	Ti
Tungsten	W
Vanadium	V
Ytterbium*	Yb
Yttrium*	Y

*** Rare-earth element**
+ Platinum group metal
[1] Helium included in 2017 list of critical raw materials, removed from 2020 list.

2 Methodology and selection of priority applications

2.1 Methodology

The assessment started with an overview of generic applications in which the presence of critical raw materials is essential for delivering functionality.

From this long list, five applications were prioritised for this analysis. The selection was based on four criteria:

- environmental impact criteria: considering carbon footprints, cumulative energy demands, non-carcinogenic toxicity for humans, carcinogenic effects for humans, terrestrial acidification and freshwater eutrophication;
- political priority: the relevance of the application in achieving the objectives laid out in EU-wide strategic programmes, plans and legislative initiatives;
- future growth/perspectives of the application from a critical raw material point of view (mass growth of the use of critical raw materials);
- knowledge gaps and feasibility in carrying out the analysis.

Prior to the criteria evaluation 13 applications using critical raw materials were screened and identified (Table 2.1).

Table 2.1 Identified applications using critical raw materials.

Application	Critical raw materials
Magnets	Cobalt, dysprosium, gadolinium, helium, neodymium, praseodymium, samarium, terbium
Batteries	Antimony, cerium, cobalt, indium, lanthanum, natural graphite, neodymium, praseodymium, silicon
Alloy/metallurgy	Beryllium, bismuth, borates, cerium, cobalt, fluorspar, hafnium, indium, magnesium, natural graphite, neodymium, niobium, praseodymium, scandium, silicon, tantalum, tungsten, vanadium, yttrium
Solar cells/photovoltaics (PVs)	Gallium, germanium, indium, scandium, silicon
Optics	Erbium, gadolinium, germanium, holmium, lutetium, samarium, thulium, ytterbium
Flat panel display	Indium
Autocatalysts and other catalysts	Cerium, cobalt, lanthanum, neodymium, palladium, platinum, praseodymium, rhodium, tungsten
Lighting	Cerium, erbium, europium, terbium, yttrium
Electronic components/parts[1]	Antimony, beryllium, gallium, helium, indium, iridium, palladium, ruthenium, silicon, tantalum, white phosphorus
Mineral fertilisers	Borates, phosphate rock
Tyres	Natural rubber
Chemicals (industrial)	Barium, bismuth, borates, fluorspar, hafnium, natural graphite, niobium, iridium, palladium, platinum, rhodium, ruthenium, silicon, tantalum, vanadium, white phosphorus

[1] The electronic components/parts composed of following sub-parts: flame retardants, integrated circuits, semiconductors, light-emitting diodes (LEDs), alloying electronics, solders, ceramic capacitors, electric components.

Catalyst for hydrogen production	Cobalt, fluorspar, iridium, lanthanum, platinum, ruthenium, tungsten, yttrium

Sources: VoltaChem (2019); European Commission (2017b)

The share of global or EU end use in the identified applications for each critical raw material was retrieved from the European Commission (European Commission, 2017b). The environmental impact per kilogram of critical raw material produced was obtained from international literature (Nuss and Eckelman, 2014) and, for the missing materials, calculated using data from Ecoinvent v2.2 (2010). To estimate the environmental impact of critical raw materials in each application, the per kilogram impact was combined with the global production and end use figures.

To map political priorities, a number of relevant European initiatives were listed and screened for references to critical raw materials in applications with a key role in the particular policy initiative. It was found that the selected applications were particularly relevant for achieving the prioritised objective of decarbonizing European energy production, reducing transport impacts, securing sustainable primary and secondary raw materials supplies for European industry, ensuring the European production of food and biomass, and meeting European security and health preservation needs.

- Several critical raw materials are essential for **decarbonizing energy production**, making the European economy less dependent on fossil fuels. Examples of European policy initiatives that target decarbonization and improved energy efficiency include the European Green Deal and A Clean Planet for all. On one hand, critical raw materials enable or facilitate harnessing energy from renewable and carbon-independent sources, such as wind, hydrogen and solar radiation. On the other, they have a role in improving energy efficiency by applying digital technologies that rely on electronic components containing critical raw materials, as for instance in smart grid development. Finally, batteries allow the temporary storage of excess energy for balancing demand and supply from combined renewable and fossil-based energy production. A recent in-depth analysis in support of the A Clean Planet for all strategy (European Commission, 2018b), however, included specific reference to the fact that "*many of critical raw materials are located in countries with poor governance and environmental standards*".
- Different strategies contained in European policy initiatives require the deployment of technologies enabling **cleaner transport**. Transport is an important sector for achieving the target of no net emissions of greenhouse gases by 2050, an aim of the European Green Deal. Applications such as batteries for electric vehicles, electronic components and tyres are relevant when facing challenges related to the provision of mobility.
- Critical raw materials are essential to e-mobility, batteries, the production of energy from renewable sources, pharmaceuticals, aerospace, defence and digital applications that are all closely connected to the European **chemical, pharmaceutical, metallurgical and manufacturing industries**. At the same time, as emphasised in A Clean Planet for all, the implementation of a coherent EU industrial policy is expected to support the transition to competitive greenhouse gas neutrality through amongst other ways the reinforcement of well-functioning internal markets for both primary and secondary raw materials, and by promoting the progressive replacement of critical raw materials. The EU long-term strategy uses trade policies to support the global competitiveness of the EU economy along different value chains, and to secure sufficient, affordable and sustainable access to raw materials, particularly critical raw materials. Securing such supplies of raw materials is believed to play an increasing role in managing risk in all EU industrial value chains. The New Industrial Strategy for Europe, which among other things supports industries in developing climate neutrality, is therefore highly important for the present analysis, since many of the technologies that enable the digital, climate neutral and circular economy transformations are highly dependent

on critical raw materials. In addition, this New Industrial Strategy for Europe considers a specific **Action Plan on Critical Raw Materials** to reinforce Europe's industrial and strategic autonomy. This Action Plan will include efforts to broaden international partnerships that facilitate access to raw materials.

- Both the New Industrial Strategy for Europe and the Circular Economy Action Plan, that were developed in parallel, consider the relevance of **recycling** raw materials as a means of reducing the EU's material consumption footprint and, at the same time, securing the supply of raw materials and lowering reliance on materials sourced from beyond the EU and for which global competition has intensified. Secondary material sources are particularly important for critical raw materials as by far the majority of those used in the EU are imported.
- Several of the material resources listed as critical raw materials relate to the **production of food and bio-based materials and energy**, especially in the application of chemicals and mineral fertilisers. The corresponding strategies include Farm to Fork and the updated European Bioeconomy Strategy (European Commission, 2018a). The latter particularly aims, amongst other things, to further exploit circular bioeconomy strategies in cities. These strategies are expected to contribute to key EU policies including those on resource efficiency and security. In this context, the conversion of urban biowaste into valuable substances is highlighted, including valuable and critical materials including phosphorus. Moreover, several countries, particularly Finland, Liechtenstein and Switzerland, have also included the recovery of phosphorus from different types of biowaste and wastewater as priorities in their national bioeconomy strategies; Switzerland plans to make the recovery of phosphorus from sewage treatment plants mandatory in 2026 (EEA, 2020).
- The focus of Smart Specialisation Strategies (European Commission, 2017a) is inherently dependent of the geographical target region and thus contains important regional diversity of priorities. Aiming for a classification of EU regions according to their Research and Innovation Strategies for Smart Specialisation (RIS3), a first categorisation for a systematic and comparative analysis of RIS3 across EU regions was carried out (Pavone *et al.*, 2019). From the 206 regions that were analysed, more than half of included digital and information and communications technology (ICT) and sustainable energy as specialisation priorities, and 47 % considered agrifood as essential for regional development. The applications that were identified for the present report and that can be directly linked with these **regional specialisation priorities** include magnets, batteries, electronic components, mineral fertilisers and hydrogen production catalysts.
- Several **defence technologies** such as batteries, magnets, electronic components, lasers, ammunition and aeronautics rely on critical raw materials (Pavel, 2016). Political priority is given to these applications in the European Defence Action Plan, in order to ensure that the European defence industrial base will be able to meet Europe's current and future security needs.

The future growth/outlook of the applications were assessed by looking at possible increases/decreases in critical raw material use through the application prospects (Monnet and Abrerrahim, 2018; Ayers, 2017; European Commission, 2017b; Guyonnet et al., 2015). The outcome of this is a five-stage, low-to-high, qualitative indicator.

Finally, the ETC/WMGE team qualitatively evaluated whether there are gaps in knowledge or/and whether carrying out the analysis was feasible.

2.2 Selection of priority applications

A summary of the results from the prioritisation of applications is presented in Figure 2-1.

Based on the outcome of the prioritisation, the following applications were selected for further analysis:

- **magnets**: notable environmental impact, relevant for political priority, high future growth;
- **batteries**: notable environmental impact, relevant for political priority, high future growth:
- **alloys/metallurgy**: high environmental impact, relevant for political priority, moderate future growth;
    - in order to carry out the analysis, **alloys in automobiles** were addressed as the application;
- **mineral fertiliser**: notable environmental impact, relevant for political priority, moderate future growth;
- **electronic components and parts**: notable environmental impact, relevant for political priority, moderate future growth;
    - due to the broad use of electronic components in different applications, the analysis focused on **printed circuit assembly**.

Application	Sector	Environmental criteria (impact/application): Carbon footprint (Kton CO_2-eq)	Cumulative energy demand (TJ)	Human toxicity (CTUh)	Acidification (Kton SO_2-eq)	Eutrophication (kton P eq)	Political priority: Green Deal	The New Industrial Strategy for Europe	Circular Economy Strategy	A Clean Planet for All	EU Bioeconomy Strategy	Smart Specialisation Strategies	Farm to Fork	European Defence Action Plan	Future growth (↑, ↓, ↔)
Magnets	Transport, energy, electronic, medical	545	10 445	256	3	0	X	X	X	X		X		X	↑ 5
Batteries	Transport, energy, electronic	1 163	16 120	17 925	15	10	X	X	X	X		X			↑ 5
Alloy/metallurgy	Transport, aerospace	131 365	528 738	31 239	97	6	X	X	X	X				X	↗ 4
Solar cells/photovoltaics (PVs)	Energy	113	2 184	165	1	0	X	X	X	X		X			↘ 2
Optics	Electronics	57	1 075	267	0	0		X						X	↗ 4
Flat panel display	Electronics, transport	45	761	752	1	0			X						↘ 2
Autocatalyst and other catalysts	Transport, chemical/energy	4 348	82 914	19 936	644	11			X						↓ 1
Lighting	Electronics, transport	327	6 402	155	1	0			X						↘ 2
Electronic components/parts	Transport, energy, electronic, medical	1 412	18 747	24 551	58	14		X	X	X		X		X	↗ 4
Mineral fertilizers	Food	17 360	308 563	3 335	72	9			X	X	X	X	X		↗ 4
Tyres	Transport	2 496	243 626	4 005	24	1			X						→ 3
Chemicals (industrial)	Various	3 203	60 330	2 775	63	3				X	X				→ 3
Catalysts for hydrogen production	Energy	0	1	0	0	0				X		X			↑ 5

Figure 2-1 Summary of results of application prioritisation ([2])

[2] The colors for each of the environmental criteria are set with a gradual color scale ranging from green (lowest environmental impact of all applications) to red (highest environmental impact). The arrows for future growth of the application are set with a five-stage scale ranging from 5 (high growth in use) to 1 (decline in use) indicating predicted increase/decrease in critical raw material use.

2.3 Methodology to determine the environmental impacts of critical raw materials in applications

It is very likely that in the foreseeable future, the use and the need for specific critical raw materials will increase in parallel with the growth of such strategic sectors as mobility, batteries, etc., since these sectors are also fundamental to ensuring a carbon neutral Europe and a low-carbon economy. In this report, environmental implications resulting from the uses of critical raw materials are analysed, particularly in light of the possibility of substituting them with more sustainable options.

In the following chapters, the environmental burdens associated with the mining, quarrying, harvesting and production of critical raw materials that are relevant to the selected applications are analysed.

The processes that carry the highest environmental burdens differ depending on the specific critical raw material. For instance, most metal lifecycles present environmental impact hotspots that are linked to the energy used in the reduction of the naturally occurring metal oxides and sulphides. At the same time, metal ore mining and beneficiation activities are likely to disturb ecosystems, due, amongst other thing, to the infrastructure needed and by dispersion of metal compounds into the environment. Damage to sensitive local ecosystems might be especially relevant in the exploitation of newly discovered resource deposits in less developed regions where the need for foreign exchange from mining concessions overshadows domestic environmental concerns (Norgate and Haque, 2010).

For other critical raw materials, for instance non-metal critical raw materials such as phosphates, the environmental hotspots might be different or be linked to different stages of their respective production processes.

Life cycle assessment (LCA) methodology currently does not fully capture the environmental effects of mining. It has weaknesses regarding ecosystem degradation, impacts on fresh- and groundwater resources and does not take disaster hazards into account. Therefore, the analysis is based on the methodology developed in the OekoRess I and II projects (Manhart et al., 2019; Dehoust et al., 2017). This method consists of indicators that allow the identification of raw material-specific environmental hotspots and rankings of raw materials. The OekoRess methodology uses the environmental hazard potential (EHP) to evaluate risks. The environmental hazard potential refers to the environmental impacts that are likely to occur if no appropriate countermeasures are taken. The following indicators are included (Manhart et al., 2019).

- Geological hazard indicators (site-specific):
  - Preconditions for acid mine drainage (AMD)
    The formation of acid waters by oxidation of ore minerals and accompanying substances. The resulting acidity of surface and ground waters is harmful as such, and also increases the solubility of other pollutants from mining residues. The element properties – lithophilic, siderophilic, or chalcophilic elements according to Victor Moritz Goldschmidt (Ferro and Saccone, 2008) – are used to assess the acid mine drainage potential.
  - Paragenesis with heavy metals
    Critical raw materials can be associated with heavy metals that are released during extraction and have a toxic effect on humans and the environment.
  - Paragenesis with radioactive substances
    Critical raw materials can be associated with radioactive elements such as uranium and thorium.
- Technical indicators (site-specific):
  - Mining method

Indicator for the intervention in the natural environment, primarily land use, vegetation destruction, changes in the hydraulic regime, etc. by the mining and the deposition of tailings and stockpiles.
  - Use of auxiliary substances
    Indicator of environmental risks related to the extraction process, procedures with toxic reagents, such as cyanidation or flotation, result in a high environmental hazard potential, for example.
- Natural environment indicators (country/site-specific):
  - Accident hazards due to floods, earthquakes, storms and landslides
    Country-specific risk of natural disasters, obtained from the Global Assessment Report on Disaster Risk Reduction Platform ([3]).
  - Water Stress Index (WSI) and desert areas
    Addresses the dangers of mining to available water resources and possible competition between water uses. The Water Stress Index at watershed level is obtained from Pfister, Koehler and Hellweg (2009).
  - Protected areas and Alliance for Zero Extinction (AZE) sites
    Indicator of the location of a mine with respect to designated protected natural areas ([4]) and AZE sites ([5]).
- Governance environment indicators (country-specific):
  - Environmental performance of the country
    Based on the 2018 Environmental Performance Index (EPI), which ranks 180 countries with respect to environmental health and ecosystem vitality (Yale Center for Environmental Law & Policy, 2018). We consider a country to have a low EHP if the EPI is below the 25 % quantile of all 180 assessed countries, and a high environmental hazard potential if the Environmental Performance Index is above the 75 % quantile.
  - In addition to the environmental hazard potential indicators, five value chain indicators based on life cycle assessment are included to estimate the total global environmental impact of producing a critical raw material for a specific application:
    - carbon footprint;
    - cumulative energy demand ([6]);
    - human toxicity impact;
    - terrestrial acidification;
    - freshwater eutrophication.

  These indicators are based on life cycle assessment of extraction, processing and refining processes. The environmental impact per kilogram of critical raw material produced was obtained from Nuss and Eckelman (2014) and Ecoinvent v2.2 (2010). To estimate the total environmental impact of critical raw materials in each application, the per kilogram impact was combined with the global production and end use share of the application. To classify the result as a low, medium or high impact, it is compared to all results obtained – impact of each critical raw material in each selected application. The impact is considered to be low if it is below the 25 % quantile of all results for the evaluated critical raw materials in their application, and high if it is above the 75 % quantile.

For the mined materials, the analysis is based on one mine per critical raw material. The aim was to select the largest mine in the largest producing country of the critical raw material, though this was not always possible due to lack of information.

[3] https://risk.preventionweb.net
[4] https://www.protectedplanet.net/
[5] https://zeroextinction.org/site-identification/2018-global-aze-map/
[6] The cumulative energy demand is not an environmental impact as such, it is however directly related to many environmental impacts generated by the use of (mainly fossil) energy throughout the lifecycle.

In most, if not all cases, critical raw materials are used in components and appliances to reduce the material needs that normally would be associated with the provision of specific and superior product functions. In wind turbines, for example, critical raw materials, more specifically rare-earth elements, allow the generators to be more efficient, resulting in smaller generators and use of fewer other resources, such as steel and composites (Vestas, 2013). In batteries, critical raw materials help achieve high energy density and thus a lighter battery. This is very important for electric vehicles, as weight affects the amount of electricity used during the operation. In these cases, the environmental benefits of the presence of critical raw materials, particularly the improved functionality in strategic areas such as communication, renewable energy production, construction, along with reduced material consumption, is expected or assumed to largely outweigh the burdens associated to the production of the critical raw material itself. Strong increased demand for specific critical raw materials, however, might affect the net environmental outcome. Nevertheless, efforts to substitute critical raw materials seem to be rarely driven by environmental concerns. In most cases, substitution aims
(i) to resolve market supply issues due to the concentration of production in a few non-EU countries, as for rare-earth elements; or
(ii) to avoid socially questionable practices, as in the case of coltan; or
(iii) to respond to an increasing risk of global resource depletion, as in the case of phosphates.

Some of the critical raw materials have hazardous characteristics, unrelated to the environmental impacts of the applied mining and production processes.

In the following chapters, environmental hotspots related to the mining and production of the critical raw materials present in the selected applications are analysed. Furthermore, for each of the selected applications, materials that often are considered as possible critical raw material substitutes are evaluated to assess whether substitution would be environmentally preferable.

This way, the following questions can be answered:

- where and what are the environmental hotspots for a certain category of critical raw material found in the selected applications;
- do any of the identified substitutes contribute to (partially) solving these environmental implications?

2.4 Methodology to determine the economic importance of an application

In this report, the economic importance (EI) reflects how the critical raw materials used in the selected applications generate economic value to the European economy. The methodology to determine EI, as used in the European Commission's 2017 assessment on critical raw material for Europe, is based on the formula below.

$$EI = \sum_s (A_s * Q_s) * SI_{EI} \qquad (1)$$

EI is the economic importance; A_s is the share of the end use of a raw material in a NACE Rev. 2 2-digit level sector; Qs is the NACE Rev. 2 2-digit level sector's value addition; SI_{EI} is the substitution index (SI) of a raw material (in economic importance); and s denotes sector. Based on Formula (1), the share of an application in the economic importance (EI) of a raw material has been derived. It should be noted that some lack of clarity in the background values generates uncertainty in the distribution, however a trend can be identified.

Self-dependency – supply chain in global production

As current markets and production are global, a worldwide crisis has major consequences on modern industry and society. As supply chains are long, disruption in any part of the chain may affect the production of the end product (Unctad, 2020). Many sectors, such as electronics and automotive industries, are likely to be impacted by supply chain delays due to the worldwide outbreak of coronavirus (COVID-19) as of March 2020 (IPC, 2020; Unctad, 2020).

From the raw materials point of view, mining operations were impacted in many countries worldwide as other industries stopped or adjusted their operations. By April 2020, mining operations in Argentina, Peru, the Philippines and South Africa had been stopped due to the global pandemic (Statista, 2020d). Further, some manufacturing industry, such as the pharmaceutical sector, expressed concern about securing the supply of critical raw materials such as phosphate (Unece, 2020).

For most of critical raw materials, the EU is dependent on imports from non-EU countries. Largest suppliers of critical raw materials to the EU are shown in Figure 2-2 based on the 2020 list of critical raw materials.

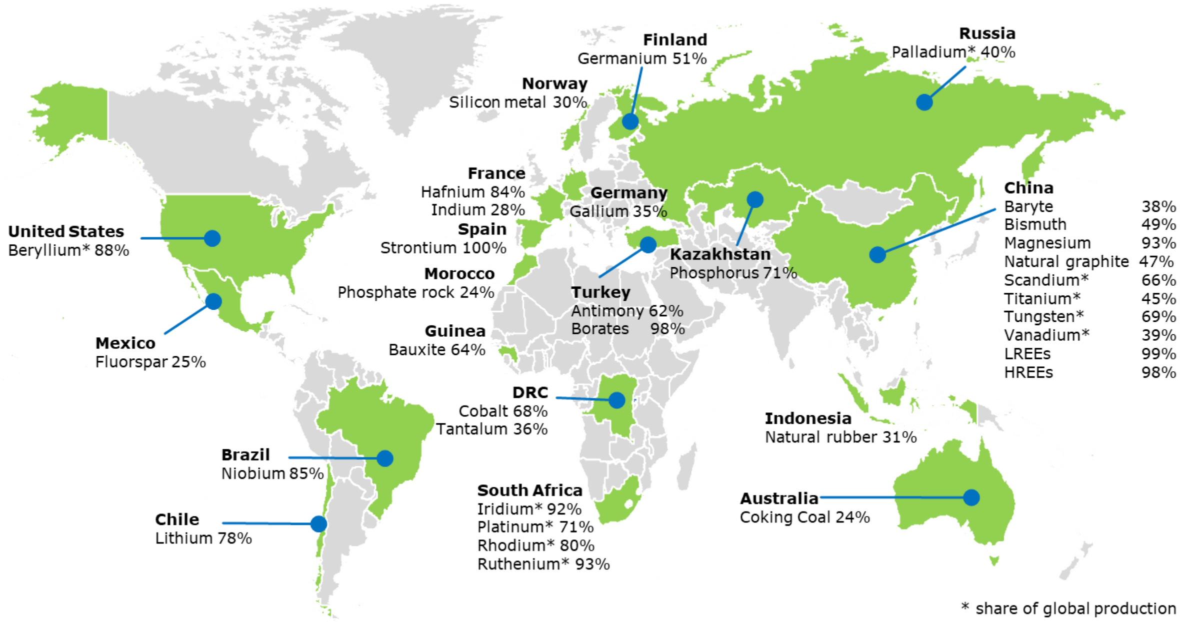

Figure 2-2 Largest suppliers of critical raw materials to the EU

Source: https://rmis.jrc.ec.europa.eu/?page=why-crms-have-a-supply-risk-8e8af9 (22.9.2020)

3 Magnets

Different types of permanent magnets are used in various applications, many of which are important for achieving a low carbon economy. Permanent magnet synchronous generators (PMSG), for example, are used in different types of wind turbines. The direct-drive low-speed turbine configuration contains the highest amount of permanent magnet and is advantageous especially for large scale wind turbines generating more than 5 megawatts (MW) and off-shore conditions. In addition, most electric and hybrid electric vehicles include permanent magnet synchronous motor technology due to its high power density and ability to create high torque (Pavel et al., 2016).

The most important permanent magnet types are ferrite, aluminium-nickel-cobalt (AlNiCo), samarium-cobalt (SmCo) and neodymium-iron-boron (NdFeB). The focus in this report is on neodymium-iron-boron magnets as they are vital for many high tech applications, and they represent a major share of the market of critical raw material-containing magnets. (Gutfleisch et al., 2011) Other types of permanent magnets are briefly covered.

Neodymium-iron-boron magnets are the strongest permanent magnets commercially available. The superior performance of these rare-earth magnets is based on the combination of 3d transition metal with 4f electron configuration of rare earth elements resulting in high magnetocrystalline anisotropy and high coercivity (Pavel et al., 2016). Thus, neodymium-iron-boron magnets are used in applications where small size and maximum power is required, including high performance applications such as wind turbines and electric vehicles, but also electric bicycles and consumer electronics (Binnemans et al., 2013). The most important end-use applications of neodymium-iron-boron magnets are presented in Figure 3-1. The downside of neodymium-iron-boron magnets is their vulnerability to corrosion and limited temperature range. The maximum operating temperature depends on the composition and ranges from 80 to 200 °C (Binnemans et al., 2018).

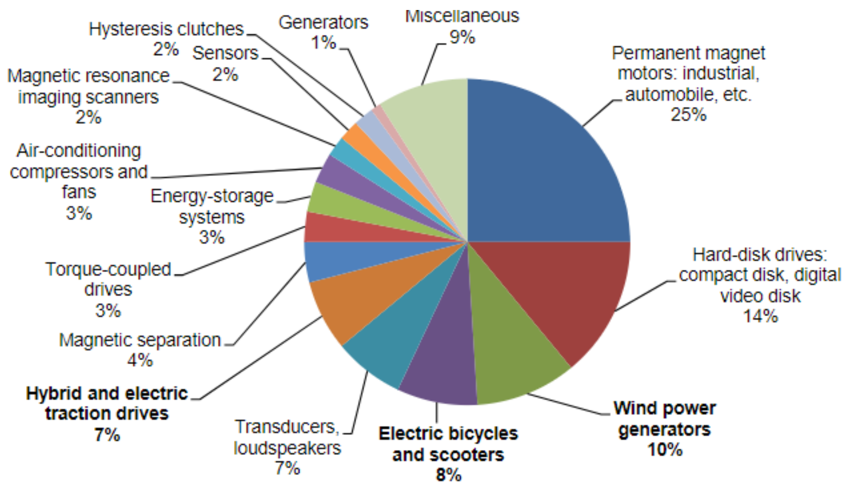

Figure 3-1 Estimated industrial end-use share of neodymium-iron-boron magnets, 2015, per cent

Source: Pavel et al. (2016)

3.1 CRMs in applications

CRMs are used in most commercial permanent magnets, and the most important critical raw materials in magnet applications as well as the share of magnets of the critical raw material end use are presented in Table 3.1.

Table 3.1 Summary of critical raw materials used in different types of magnet

CRM	Magnet type	Share of magnets in critical raw material end uses (EU, except for Gd and Co), by weight
Neodymium	NdFeB	37 %
Praseodymium	NdFeB	24 %
Gadolinium	NdFeB	35 % (global)
Dysprosium	NdFeB	100 %
Terbium	NdFeB	32 %
Samarium	SmCo	97 %
Cobalt	SmCo, NdFeB, AlNiCo	5 % (global)

Source: European Commission (2017b)

Neodymium-iron-boron (NdFeB) magnets are the most important type of permanent magnet used in high-tech applications, more specifically $Nd_2Fe_{14}B$. These magnets are mainly composed of iron, neodymium and boron, where neodymium can be partly substituted with dysprosium, terbium and gadolinium, and iron can be partly substituted with aluminium, copper and cobalt (European Commission, 2017b; Y. Yang et al., 2017). The exact composition of the neodymium-iron-boron magnet depends on the requirements of the end-use application. An example of the composition for room temperature applications is shown in Table 3.2.

Table 3.2 Example a composition of a neodymium-iron-boron magnet for room temperature applications

Main elements in NdFeB	Weight %
Neodymium (and/or praseodymium)	29–32
Iron	64.2–68.5
Boron	1.0–1.2
Aluminium	0.2–0.4
Dysprosium (and/or terbium)	0.8–1.2

Source: Bunting (https://e-magnetsuk.com/neodymium_magnets/neodymium_magnets_made.aspx)

The amount of rare-earth elements in neodymium-iron-boron magnets is typically 31–32 % by weight, the majority of which is neodymium and praseodymium (Yang, Y. et al., 2017). The amount of praseodymium varies and can be up to ratio of neodymium to praseodymium of 4:1 (Pavel et al., 2016). Dysprosium and terbium are used as additives to increase the Curie temperature ([7]) of the neodymium-iron-boron magnet and thus the operating temperature up to 200 °C. The required amount of Dy and Tb depends on the application and can be up to 3-7 % in wind turbines and 9 % in EVs (Tercero et al., 2018). However, the addition of dysprosium and terbium also decreases the remanence and the energy density (Yang, Y. et al., 2017), and increases the cost of the magnet. Thus, the usage of dysprosium and terbium in higher amounts is restricted only to applications where high temperature stability is required. Small amounts of gadolinium also improve the temperature coefficient and thus the high temperature performance (Yang, Y. et al., 2017). Other rare-earth elements have also been studied as partial substitutes for neodymium or iron to alter the properties and increase the performance of the neodymium-iron-boron magnet including lanthanum, cerium, niobium and gallium (Yang, Y. et al., 2017; Yan et al., 2012).

[7] the temperature above which certain materials lose their permanent magnetic properties

Typical quantities of neodymium-iron-boron magnets needed in different applications are compared in Table 3.3 (Pavel et al., 2016).

Table 3.3 Some applications using neodymium-iron-boron magnets and permanent magnet amounts involved

Application	Typical neodymium-iron-boron magnet amount in application
Wind turbines	
direct drive	high, 650 kg/MW
geared	low-medium, 80–160 kg/MW
Electric vehicles	
with permanent synchronous motor (PSM)	1–2 kg/EV (less for HEVs)
Electric bicycles	0.3–0.35 kg/bike

Source: Pavel et al. (2016)

Samarium-cobalt (SmCo) magnets, more specifically $SmCo_5$ or Sm_2Co_{17}, are alloys of mainly samarium and cobalt. In Sm_2Co_{17} composition, cobalt can be partly substituted with iron, zirconium and copper. Samarium-cobalt magnets have the advantage of high temperature performance even up to 400 °C as well as good corrosion resistance. However, the high price of samarium and complex production process has limited the use of samarium-cobalt magnets to specific applications with only a minor market share (Pavel et al., 2016; Binnemans et al., 2013). These magnets are the main end-use application for samarium with 97 % of the end use occurring in the EU (European Commission, 2017b).

Aluminium-nickel-cobalt (AlNiCo) magnets are based on alloys composed mainly of aluminium, nickel, cobalt and iron. These magnets possess the highest operating temperature, up to 500 °C, but they suffer from low coercitivity when compared to neodymium-iron-boron and samarium-cobalt magnets. Thus, their use is limited to lower-value applications with a very limited market share (Pavel et al., 2016; Gutfleisch et al., 2011).

In terms of volume, ferrite magnets constitute a major share of permanent magnet sales due to their low price and simple production process (Kumar, 2017; Gutfleisch et al., 2011). These magnets mainly comprise of ferric oxide, but often also contain strontium (Sr) or barium (Ba) or both, the most common formulations being $SrFe_{12}O_{19}$ and $BaFe_{12}O_{19}$ (Riba et al., 2016). Some commercially available ferrite magnet grades contain lanthanum or cobalt to improve the magnetic properties ([7]).

3.2 Economic importance and future aspects

3.2.1 Economic importance

In this report, the economic importance reflects how critical raw materials used in the application generate economic importance to the European economy based on the EC's 2017 assessment of critical raw materials. The distribution of economic importance of critical raw materials used in magnets is presented in Figure 3-2. It describes the share of the application in the economic importance of these particular critical raw materials.

[7] https://e-magnetsuk.com/ferrite_magnets/ferrite_magnets_made.aspx

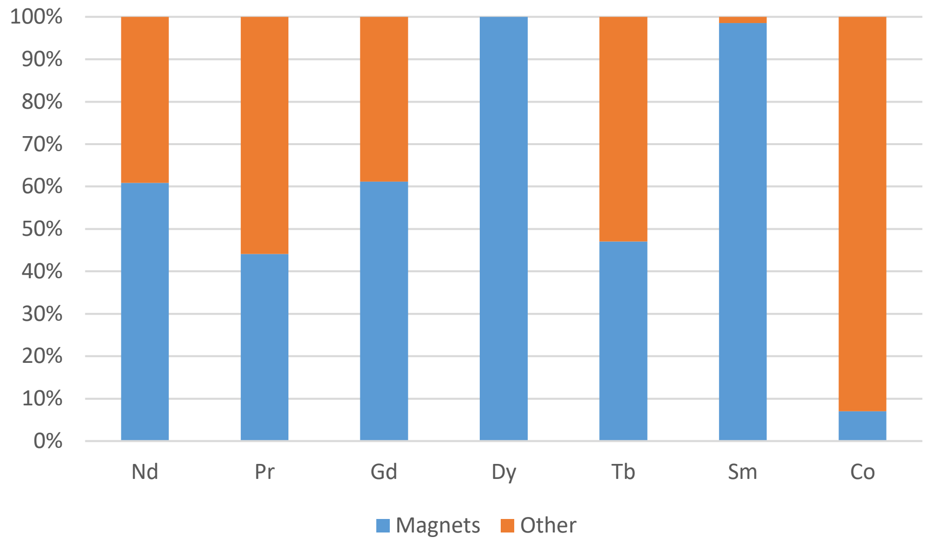

Figure 3-2 The contribution of magnets to the economic importance of critical raw materials, per cent

Source: ETC/WMGE based on European Commission (2017b)

From Figure 3-2 it can be seen that magnets are important applications for many critical raw materials. For neodymium, gadolinium, dysprosium and samarium magnets generate over half their economic importance whereas for praseodymium and terbium it is slightly below 50 %. In the case of cobalt, magnets are not one of the main applications even though it is used in samarium-cobalt magnets which generate significant economic importance for samarium.

As a whole, magnets can be considered as one of the key applications, used in several sectors such as energy, transport and electronics.

Wind turbines

Neodymium-iron-boron (NdFeB) magnets are used in wind turbines with permanently excited synchronous generators and direct drives which are usually used in offshore installations. In 2019, 3,627 new offshore installations, 27.5 % of all installations, were built in the EU28. In terms of total cumulative capacity, offshore installations account for 22 gigawatts (GW), representing 11.5 % of the total installed wind power capacity (Wind Europe, 2019c). There is a trend of increasing offshore installations, which may also reflect on the permanent magnet demand.

Five offshore wind turbine manufacturers have supplied 99.1 % of cumulative installations in the EU – Siemens Gamesa Renewable Energy, 68.1 %; MHI Vestas, 23.5 %; Senvion, 4.4 %; Bard Engineering, 1.6 %; and GE Renewable Energy, 1.5 % (Wind Europe, 2019a).

In terms of the global and yearly market of leading offshore wind power companies, Siemens was the leader with 60.5 % market share followed by Vestas with 13.4 % share in 2018 (Statista, 2019).

Electric vehicles

The electrification of the transport sector is one of the key actions in the mitigation of climate change. Beside batteries, electric vehicles also require permanent magnets in their synchronous motors. The market share of electric vehicles (plug-in hybrids and battery electric vehicles) has increased in Europe from slightly below 1 % of the total market in 2015 to roughly 3 % in 2019 (Statista, 2020a). The share will continue increasing in the coming years.

The best-selling electric vehicle models in Europe in 2019 were the Tesla Model 3, 95,170 cars sold; the Renault Zoe, 45,130; and the Mitsubishi Outlander plug-in hybrid electric vehicle (PHEV), 34,600 (Statista, 2020a).

3.2.2 Future aspects

The generation of electricity by wind power is expected to increase in the future as it plays a significant role in meeting Europe's climate and energy goals. According to Wind Europe, an additional 88 GW of net capacity could be installed in Europe, bringing to overall total capacity to 277 GW in 2023 (Wind Europe, 2019b). At least 75 % of the new installations are expected to be onshore ones (Wind Europe, 2019b).

As for the critical raw materials used in wind generators, Gislev et al. (EC, 2018) have estimated that by 2030 the demand for dysprosium, neodymium and praseodymium will be around 3.25 times higher than it was in 2015 in a low-growth scenario and around 44 times higher in a high-growth scenario. In 2015, the demand for dysprosium, neodymium and praseodymium was 71,356 and 119 tonnes respectively. Substitution and recycling have been identified as the most effective measures to enhance the EU supply of these critical raw materials (Blagoeva et al., 2016).

As electric vehicles enter the vehicle fleet, reducing emissions from transport, the demand for electric motors and consequently permanent magnets will increase. According to Statista, in 2030 16.5 million electric vehicles will be produced in Europe (Statista, 2020b) and it has been estimated 3.9–13.0 % of new car registrations in 2030 will be battery electric vehicles (BEVs) and 6.7–22.1 % plug-in hybrid electric vehicles. This is significant increase on new registrations both for battery electric and plug-in hybrid electric vehicles which accounted for only 1.5 % of the total market in 2017 (EEA, 2018).

In terms of the future demand for magnets in electric traction motors, the EC has estimated that in 2030 the demand for dysprosium and praseodymium would be around 9.4 times higher than the 27 tonnes used in 2015 and for neodymium, it is expected to be 9.5 higher than the 80 tonnes used in 2015 (EC, 2018). As for wind generators, substitution and recycling have been identified as the most effective measures to enhance the EU supply of dysprosium, neodymium and praseodymium for traction motors (Blagoeva et al., 2016).

3.3 Environmental aspects

3.3.1 Risks and impacts of critical raw materials in applications

This section focusses on virgin critical raw materials used in magnets, as currently almost no recycling takes place (Wulf et al., 2017). The environmental hazard potential of extraction and production of the main critical raw materials used for magnets – rare-earth elements, boron and cobalt −, is presented in Table 3.4. All critical raw materials present high environmental hazard potential for two or three indicators. All have a high pollution risk at the mining site, for rare-earth elements there is a high natural accident hazard and for boron there is a high risk that its mining could causing water stress. All are mined from open-cast mines, which has a direct impact on the environment as a result of the removal of topsoil and vegetation. If no appropriate measures are taken to limit these risks, environmental impacts are very likely to occur. Since most of these critical raw materials are produced in countries with medium or low environmental performance index scores, it is probable that all necessary measures are not taken.

Table 3.4 Evaluation of the environmental hazard potential of critical raw materials in magnets ([8])

	Goal	Indicator	Rare-earth elements	Boron	Cobalt
			Bayan Obo, China	Bigadiç, Turkey	Katanga, DRC
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Lithophylic elements	Lithophylic element in colemanite, tincal and ulexite	Siderophilic element, mostly oxidised with sulphides in some sections
		Paragenesis with heavy metals	Soil in the mining area of Bayan Obo has been found to be contaminated with chromium, cadmium, lead, copper, and zinc	Groundwater in the mining area has been found to be contaminated with arsenic	Cobalt is associated with copper
		Paragenesis with radioactive components	0.16% thorium oxide, also uranium	No indications that boron is associated with elevated levels of uranium and thorium	No information found on levels of uranium and thorium in Mutanda, however, radioactive elements are present in other cobalt deposits in DR Congo
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Extractants such as D2EHPA, TBP, and aliquat 336 have been widely used ([9])	Extraction generally involves acid	Extraction involves acid
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	Turkey: medium natural accident hazard	DR Congo: low natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	High water stress	Low water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	Very close to Marungu Highlands AZE site

[8] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

[9] D2EHPA, di-(2-ethylhexyl)phosphoric acid; TBP, tributyl phosphate; aliquat 336, N-Methyl-N,N,N-trioctylammonium chloride

	Goal	Indicator	Rare-earth elements	Boron	Cobalt
			Bayan Obo, China	Bigadiç, Turkey	Katanga, DRC
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium Environmental Performance Index	Turkey: medium Environmental Performance Index	DR Congo: low Environmental Performance Index
Value chain	Carbon footprint (Kton CO_2-eq/application)		5.6E+02	4.1E-01	5.6E+01
	Cumulative Energy Demand (TJ/application)		1.1E+04	7.5E+00	8.7E+02
	Human toxicity, cancer and non-cancer (CTUh/application)		2.6E+02	7.7E-02	2.6E+01
	Terrestrial acidification (Kton-SO_2 eq/application)		2.4E+00	1.8E-03	6.0E-01
	Freshwater eutrophication (Kton P-eq/application)		2.2E-01	1.5E-04	2.7E-02

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([10]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([11]), AZE sites: 2018 - 2020 American Bird Conservancy ([12]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), rare-earth elements: Ferro and Saccone, 2008; Koltun and Tharumarajah, 2010; Xie et al., 2014; Pan and Li, 2016; Liu et al., 2018, boron: Kar, Şen and Demirbaş, 2006; Gemici et al., 2008; Kuskay and Bulutcu, 2011, cobalt: Golder Associates, 2011; Shengo, 2018, Mindat.org ([13]), Glencore ([14])

Rare-earth elements, such as dysprosium, neodymium, praseodymium and samarium, are major components of neodymium-iron-boron and samarium-cobalt permanent magnets. The production of rare-earth elements causes significant environmental damage, as it is material and energy intensive and generates large amounts of emissions to air and water, and solid waste (Navarro and Zhao, 2014). Their production in China, the largest producer, has raised environmental concerns with regards to heavy metal and radioactive emissions to groundwater, rivers, soil and the air around mine sites (Navarro and Zhao, 2014). Additionally, the roasting phase of ores has an impact due to the large quantity of heat required, which in China is supplied by coal (Zaimes et al., 2015).

More than half of all cobalt is mined in the Democratic Republic of the Congo (DRC), which is reported to be problematic from an environmental and social point of view (van den Brink et al., 2020). For example, child labour is reported to be common in artisanal and small-scale mining in the DRC (O'Driscoll, 2017), while exposure to cobalt can lead to health problems in the mining communities (Dunn et al., 2015). Environmental issues reported include contamination of soil with heavy metals, wetland acidification, biodiversity loss, vegetation die back and soil erosion (Dunn et al., 2015). Cobalt-dominant mines also extract arsenide ores, which can lead to additional environmental and human health issues (Dunn et al., 2015). Almost half of the world's cobalt is refined in China (van den Brink et al., 2020). Some of the potential environmental issues of cobalt refining are the energy intensity of

[10] https://risk.preventionweb.net/
[11] https://www.protectedplanet.net/
[12] https://zeroextinction.org/site-identification/2018-global-aze-map/
[13] https://www.mindat.org/loc-294223.html
[14] https://www.glencore.com/dam/jcr:851138e1-268a-4554-ad03-c6b8dea21308/Glencore-Sell-Side-Analyst-Visit-Mutanda-201311.pdf

the processes (Farjana et al., 2019) aggravated by the largely coal-based Chinese electricity production and the CO_2 emissions released due to thermal decomposition during the last step (calcination) of the battery-grade cobalt oxide powder production (Dai et al., 2018).

Improper management of waste from borate mining operations in Turkey has led to the pollution of surface and ground water with boron and arsenic (Omwene et al., 2019). The arsenic pollution is specific to the Emet and Orhaneli stream basins, as colemanite that contains arsenic minerals is mined (Omwene et al., 2019).

3.3.2 Impact of applications from a lifecycle perspective

The environmental impacts of the production of neodymium-iron-boron magnets are mainly caused by the critical raw materials, more specifically the rare-earth elements (Jin et al., 2018; Marx et al., 2018), which, depending on the impact category, contribute 50–100 % of the total impact (Jin et al., 2018; Marx et al., 2018). These authors also found that the impact of the rare-earth elements differs largely depending on the production site. The environmental impacts of rare earth oxides from Bayan Obo, China were the highest, while those of Mount Weld, Australia and especially Mountain Pass, California, United States, which closed in 2015, were much lower (Marx et al., 2018). The environmental impact of mining other critical raw materials – cobalt, boron, gallium – is minimal (Jin et al., 2018).

The critical raw materials, especially the rare-earth elements, thus contribute significantly to the environmental impact of magnets. The impact of the magnets themselves, however, is not necessarily large compared to the total environmental impact of the end-use application. Nordelöf et al. (2019) investigated the environmental impact of an electric vehicle traction motor and found the contribution of neodymium-iron-boron and samarium-cobalt magnets was limited, except for resource depletion, depending on the method, and that the overall environmental impacts were largely the result of the production of the rest of the motor and its use (Nordelöf et al., 2019). In the use phase, the authors only include the electricity needed to overcome losses caused by the motor, for example in carrying its own mass. The contribution of the critical raw materials in a magnet to the climate change impact of an electric-vehicle motor is shown in Figure 3-3. Nordelöf et al. (2019) note that the magnets influence the environmental impact in a rather indirect way, as their properties have an effect on the quantity of other materials used in the motor design.

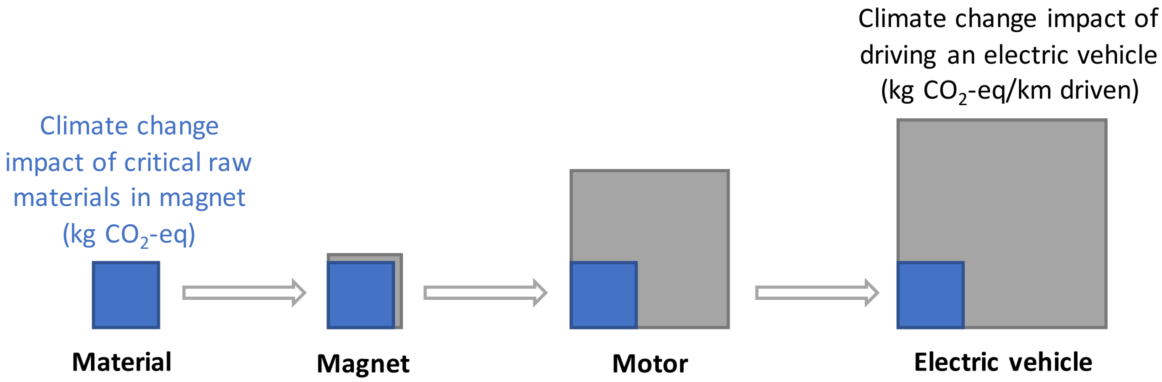

Figure 3-3 The contribution of the critical raw materials in a magnet to the impact on climate change of the final application in an electric vehicle ([15])

Source: based on Nordelöf et al. (2019) and Jin et al. (2018)

Magnets are often used in applications that are intended to lower climate impacts. The use of magnets in electric and hybrid electric vehicle motors, for example, can facilitate the transition to transportation with a lower carbon footprint. Most LCAs on electric vehicles conclude that they have lower lifecycle greenhouse gas emissions than vehicles with combustion engines (EEA, 2018). The climate change impact of the production stage of an electric car is higher than its traditional equivalent, but the impact of driving it is lower (Helmers et al., 2020; Kawamoto et al., 2019). Therefore, after driving a certain distance, the climate change impact of an electric vehicle starts to become lower than that of a combustion engine vehicle. This break-even point depends on many factors, such as the electricity used to charge the battery, the battery size and the country of battery production (Helmers et al., 2020; Kawamoto et al., 2019). According to Helmers et al., (2020), the break-even point for an electric Volkswagen Caddy at which it begins to have a lower climate change impact ranges from 17,000 to 310,000 kms. The fact that the battery of an electric vehicle will have to be replaced at some point also needs to be taken into account, as this may lead to the climate change impact of the electric vehicle surpassing that of the combustion engine vehicle again (Kawamoto *et al.*, 2019). Under optimised conditions for battery production and using renewable electricity to charge the battery, the climate change impact of an electric vehicle is about a third of a combustion engine vehicle over a lifetime of 150,000 kms (Helmers et al., 2020). For environmental impacts other than climate change, the picture is mixed, with electric vehicles potentially having a higher impact than vehicles with combustion engines in terms of, for example, human toxicity and freshwater ecotoxicity (EEA, 2018). Since the environmental impact of the critical raw materials in magnet production for electric vehicles is small compared to the total impact of the vehicle's lifetime, the focus should be on using the critical raw materials in an optimal way to reduce the weight of the vehicle, rather than just trying to minimise their use. Reducing the weight of the vehicle can achieve significant environmental savings over the its lifetime, depending on the energy used for charging.

Permanent magnets are also used in wind turbines but, in general, account for a small share of the environmental impacts of the total wind turbine. Additionally, rare earths elements allow making the generators more efficient, which results in smaller generators and therefore less use of other

[15] The first block shows the greenhouse gases emitted during the production of the critical raw materials needed to deliver the final function – driving an electric vehicle. In the next stages of the lifecycle, the greenhouse gases that are related to other materials, energy use, direct emissions and waste are added. Data on the greenhouse gas emissions were obtained from Nordelöf et al. (2019) and Jin et al. (2018). The calculations are based on a neodymium-iron-boron magnet, only electricity from the Swedish grid needed to overcome losses caused by the motor is included in the use phase. The share of the critical raw materials in magnets in the total climate change impact of driving an electric vehicle is about 9 %.

resources, such as steel and composites (Vestas, 2013). This may not be, however, the case for mineral resource depletion, where the neodymium-iron-boron magnet in the direct drive permanent magnet synchronous generator is responsible for most of the impacts (Schreiber et al., 2019). Nevertheless, wind power generally emerges as the energy technology with the lowest environmental impact (Laurent et al., 2018). Its contribution to many environmental issues, such as climate change, is significantly lower than that of fossil energy. In terms of resource depletion, on the other hand, the impact of wind turbines may be higher than that of fossil energy due to the use of rare metals (Laurent et al., 2018). In addition to the permanent-magnet generators, magnets can also be used in wind turbine towers. According to Vestas, using about 14 kilograms of neodymium in the tower magnets of a wind turbine results in a saving of approximately 10 tonnes of steel, generating a saving of around 8 tonnes of carbon dioxide equivalents over the lifecycle of the wind turbine (Vestas, 2013).

3.4 Substitution solutions

Two possible routes can be applied to reduce the amount of critical raw materials in neodymium-iron-boron magnets: first, by the partial substitution of neodymium and praseodymium, and second, using critical raw material-free, alternative magnet technologies; both are the subject of a number of research activities (Tercero et al., 2018).

3.4.1 Partial substitution of rare-earth elements in neodymium-iron-boron magnet configurations

Current research aims to reduce the quantity of rare-earth elements in neodymium-iron-boron magnets instead of their full substitution (Omodara et al., 2019). A significant reduction of neodymium and praseodymium in neodymium-iron-boron magnets in the next decade, however, is not likely (Lacal-Arántegui, 2015).

The attempts to substitute rare-earth elements in neodymium-iron-boron magnets include a partial co-doping of neodymium with cerium and iron with cobalt, which has been reported to eliminate the need for doping the alloy with dysprosium and is claimed to result in a high-strength permanent magnet comparable to the conventional neodymium-iron-boron one (Pathak et al., 2015). Dysprosium is used in neodymium-iron-boron magnets to prevent it from demagnetising at elevated temperatures by improving its heat stability (Smith and Eggert, 2018). The evident weakness of this substitution solution is that also the substitutive elements are critical raw materials, although it is claimed that cerium is more abundant than neodymium or praseodymium (Pathak et al., 2015). A similar approach has been presented in which part of neodymium is substituted by lanthanum and cerium (J. Jin et al., 2016).

Another approach allowing a reduction of the dysprosium content involves a manufacturing technique using a novel process that has been demonstrated by Hitachi Metals in which dysprosium is diffused into the magnet material instead of direct alloying (Widmer et al., 2015).

3.4.2 Substitutive magnet technologies

The currently available alternatives to neodymium-iron-boron magnets are based on samarium-cobalt and aluminium-nickel-cobalt ones, which also use critical raw materials, as discussed above. Moreover, these alternatives also exhibit inferior performance in terms of, for instance, magnetic properties (Omodara et al., 2019).

Ferrite magnets are another group possibly capable of replacing neodymium-iron-boron magnets in some applications. These mainly comprise of ferric oxide but also often contain strontium or barium or both. Ferrite magnets are assumed the most promising candidates to substitute neodymium-iron-boron magnets in electric vehicle motors (Riba et al., 2016).

Iron nitride, more specifically α”-$Fe_{16}N_2$, is claimed to be one of the most promising rare-earth element-free magnet candidate that could be used in relatively low-temperature, below 150 °C, applications (Wang, 2019). Another group of permanent magnets that have attracted attention are manganese-based compounds, especially manganese alloyed with aluminium, gallium or bismuth (Yang et al., 2018).

3.4.3 System-level substitution or component substitution

Neodymium-iron-boron (NdFeB) magnets used in electric traction motors allow very strong magnetic fields to be generated from very small volumes. The alternative approach is to generate magnetic fields with electromagnets by passing current through a conducting coil (Widmer et al., 2015). In this case, the motors are designed differently from those that use neodymium-iron-boron magnets (Omodara et al., 2019). Although many of the electric motors for electric vehicles rely on employing rare-earth element based permanent magnets, most often on synchronous permanent magnet rotors, there are different possibilities of developing electric motors without them (Riba et al., 2016), as Figure 3-4 demonstrates.

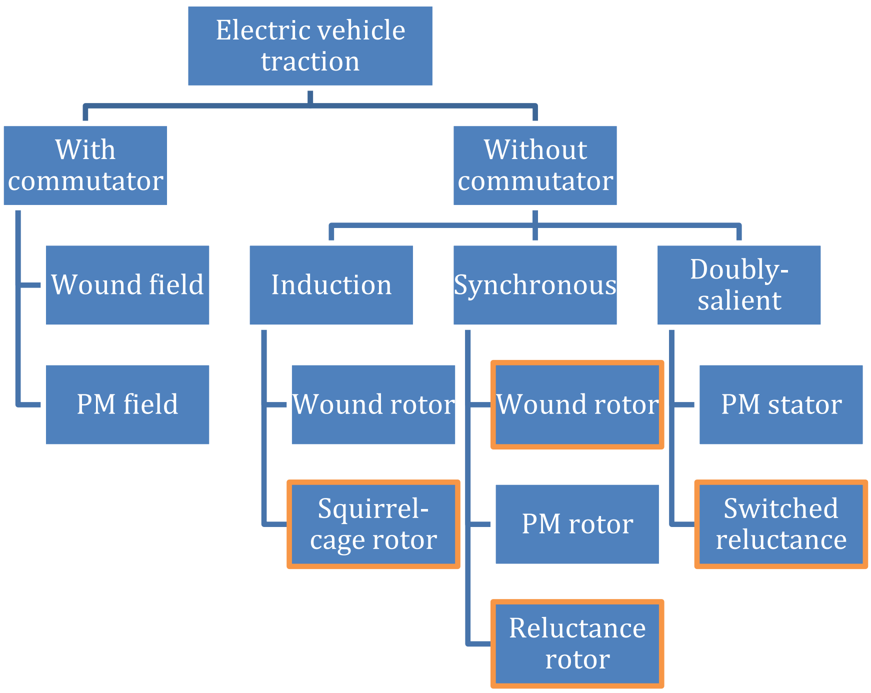

Figure 3-4 Types of electric motors

Note: PM designates permanent magnet. Orange border highlights the types compared in Table 3.5
Source: Sandeep and Shastri (2019)

It has been reported that some of the rare-earth element-free motors are able to achieve similar performance in terms of, for example, torque density and efficiency, compared to the state-of-the-art rare-earth based electric motors (Riba et al., 2016). Table 3.5 presents a comparison of some of these motor types.

Table 3.5 Types of motors free of rare-earth element based magnets

Motor type	Advantages	Disadvantages	Examples of commercial use
Squirrel-cage type induction motor (asynchronous motor)	Ease of design, low maintenance, low cost, reliability, ruggedness	Difficulty of low-speed operation control, low efficiency, risk of overheating	Mercedes-Benz, Toyota, Tesla
Synchronous wound rotor motor	High starting torque	Complexity of system, high cost, risk of overheating	Renault
Synchronous reluctance motor	Ease of production	Low efficiency, low power factor and low torque density	ABB (industrial applications)
Switched reluctance motor	Ease of design, production and assembly, low cost, low inertia, good thermal properties, high torque density, robustness	Complex control, low efficiency, strong vibration, acoustic noise	Rocky Mountain Technologies, US Motors (industrial applications)

Source: Omodara et al., (2019); Widmer et al. (2015)

Wind turbine generators are another important application area for permanent magnets, in which component substitution is possible. As a matter of fact, the most common turbine technology without permanent magnets, doubly-fed induction generators (DFIGs) using electromagnets, was developed before technologies relying on permanent magnets, such as permanent magnet synchronous generators (PMSGs) (Pavel et al., 2016). Figure 3-5 shows the classification of these and other principal wind turbine types.

Even though the DFIG is still the most common generator type in wind turbines in general, the PMGS is the more preferred option in over 5 MW generators and in off-shore wind turbines due to the higher maintenance costs and lower efficiency of DFIGs compared to PMGSs (Smith and Eggert, 2018; Pavel et al., 2016). Examples of commercial use of wind turbine generators without permanent magnets include DFIGs employed by Senvion and electrically excited synchronous generators (EESGs) used by Enercon (Pavel et al., 2016).

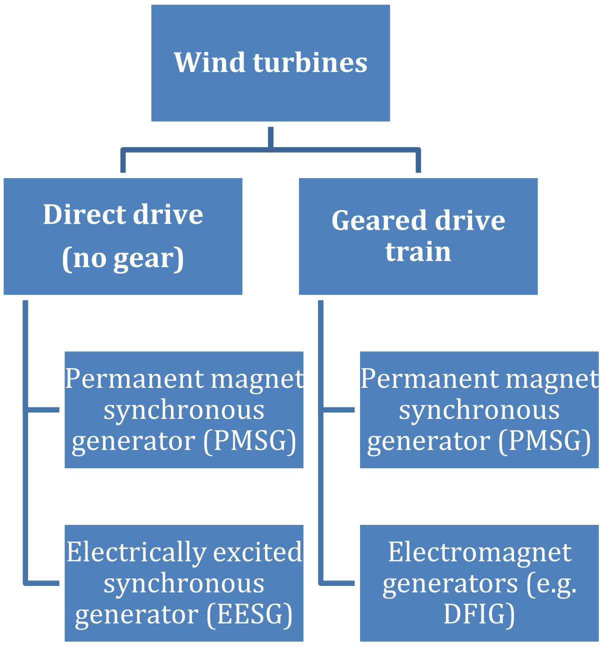

Figure 3-5 Classification of the most common wind turbine types

Source: Pavel et al. (2016)

3.4.4 Secondary raw materials

This section focuses on the availability of neodymium and praseodymium from secondary resources, namely the recycling from neodymium-iron-boron magnets and NiMH batteries.

Neodymium-iron-boron (NdFeB) magnets in hard-disk drives (HDDs) have been seen as one of the most promising sources of secondary neodymium due to the large quantities produced (Omodara et al., 2019; Widmer et al., 2015). However, hard-disk drives have lately been partly replaced by solid-state disks (SSDs) (Binnemans et al., 2013) that do not contain magnets (Data Security Inc., 2014). In 2017, it was estimated that the production of solid-state disks in 2020 would approach that of hard-disk drives, reaching 320 million solid-state disks in comparison to 350 million hard-disk drives (Statista, 2017).

The recovery of neodymium from hard-disk drives is, however, challenging: the collection and sorting of HDDs and the efficient separation of neodymium-iron-boron magnets from other materials have both proved difficult (Omodara et al., 2019). On laboratory scale, high recovery rates can be achieved, as Table 3.6 shows, but according to Reimer et al. (2018), no commercial recycling of rare-earth elements from HDDs or other neodymium-iron-boron magnet applications was in operation in the EU and that sufficient volumes of neodymium-iron-boron waste to feed commercial recycling, above 1,000 tonnes per year, cannot be expected in the EU before 2033. Nonetheless, they anticipate that the slow increase of available neodymium-iron-boron waste will allow the scaling-up of recycling processes currently under development (Reimer et al., 2018).

Very little information is available on recycling of neodymium-iron-boron magnets other than from hard-disk drives and e-waste. Wind turbines, for example, could provide considerable potential for rare-earth element recovery. It should, however, be noted that the lifetime of wind turbines is quite long, 25–30 years, and their recycling is thus not able to reduce the demand from primary sources in the short or medium term (Habib and Wenzel, 2014).

Table 3.6 Recovery techniques for critical raw materials from different end-of-life applications

CRMs	Application	Recovery technique	Yield of recovery
Neodymium, praseodymium	NiMH batteries	Leaching	97–98 % for neodymium, 89% for praseodymium
Neodymium	Hard-disk drives	Leaching	95 %
Neodymium, praseodymium	NdFeB magnets in electronic waste	Direct melting	28 % for neodymium, 1 % for praseodymium
Neodymium, praseodymium	NdFeB magnet scrap	Molten salt extraction	87% for neodymium, 89 % for praseodymium

Source: Omodara et al. (2019)

Neodymium and praseodymium, along with cerium and lanthanum, can also be recovered from end-of-life NiMH batteries. This is done commercially by Umicore employing a pyrometallurgical technique and by Japan Metals & Chemicals by using a molten salt electrolysis (Forbes, 2014; Omodara et al., 2019).

3.4.5 Environmental impacts

High-performance rare-earth element free magnets are currently not available (Barros et al., 2019) although some attempts have been made to (partially) replace neodymium and praseodymium in neodymium-iron-boron magnets by other, more abundant rare-earth elements such as cerium and lanthanum. This is not done for environmental reasons and does not eliminate environmental risks, as these critical raw materials are mined at the same sites. The total environmental impact of the critical raw material production for magnets might decrease as the higher concentration of cerium and lanthanum in ore (Haque et al., 2014) means that less ore would need to be mined and processed to produce the same mass of critical raw material. This, however, depends on the quantity of cerium and lanthanum needed to replace neodymium and praseodymium and on the effects this may have on the performance of the magnets. For example, if the magnet with cerium and lanthanum is heavier, this increases the energy consumption of an electric vehicle in the use phase, which may nullify the environmental gains achieved in the production of the magnets. Research on (partial) substitution of rare-earth elements in neodymium-iron-boron magnet configurations is at an early stage, therefore no life cycle assessments of the corresponding effects could be found.

Even though the goal is not to reduce environmental impacts, system-level substitution may be better for the environment in some cases. Nordelöf et al. (2019) compared the environmental impacts of electric vehicle traction motors with three different core designs:
(1) a permanent magnet synchronous machine (PMSM) with neodymium-iron-boron magnets;
(2) a permanent magnet synchronous machine with samarium-cobalt magnets; and
(3) a permanent magnet-assisted synchronous reluctance machine (PM-assisted SynRM) with strontium-ferrite (Srferrite) magnets.

Strontium-ferrite magnets generally do not contain critical raw materials. The comparison is made per kilometre driven. The authors, Nordelöf et al. (2019), found that the PM-assisted SynRM with strontium-ferrite magnets are the most efficient, resulting in a lower impact in the use phase and the lowest emissions of carbon dioxide equivalents. The production of a strontium-ferrite magnet also has a smaller impact on climate change than neodymium-iron-boron and samarium-cobalt ones, but this impact is minor compared to the impact of the motor production and use phase (Nordelöf et al., 2019). Similar results are found for almost all impact categories studied; PM-assisted SynRM magnets perform best due to their lower impact in the use phase, while a permanent magnet synchronous machine with neodymium-iron-boron magnets and a permanent magnet synchronous machine with samarium-cobalt magnets have about the same impact (Nordelöf *et al.*, 2019).

No studies on the environmental impacts of other alternatives to neodymium-iron-boron magnets in electric vehicles were found, though some life cycle assessments of these motors for industrial applications are available. As mentioned above, many are less efficient than neodymium-iron-boron magnets, which can result in higher overall impacts for the application, even if the impacts of the manufacturing of magnets or alternative systems are lower.

For wind turbines, Ozoemena et al. (2018) evaluated different opportunities for technological improvement. One of these is the replacement of copper-wound rotors by permanent magnet generators. The authors found that, in all impact categories, the impact of a turbine with a permanent magnet generator is lower than one with copper-wound rotors due to the high energy intensity of copper (Ozoemena et al., 2018).

Secondary raw materials

By recycling neodymium-iron-boron magnets, the most environmentally detrimental aspects of their production processes, including mining, beneficiation, leaching and solvent extraction, can be reduced (Jin et al., 2016). By magnet-to-magnet recycling, at least 90 % of the rare earth elements can be recovered (Jin et al., 2016), reducing the impact, depending on the impact category, by 64−96 % compared to virgin magnets (Jin et al., 2018).

4 Batteries

Electrochemical energy storage devices are essential for achieving a low carbon economy as both electric vehicles and renewable energy sources – wind and solar – rely on the use of rechargeable battery technologies. This report concentrates on rechargeable lithium ion batteries in electronics, electric vehicles and stationary energy storage applications. Nickel metal hydride (NiMH) batteries are also briefly discussed due to their use of critical rare earth elements. Other types of batteries containing critical raw materials – lead acid batteries with antimony as an additive, and alkaline batteries with indium as one alternative to mercury – are not covered in this report.

The highest growth in the lithium-ion battery (LIB) market in the near future is expected in the electric vehicle and stationary storage sectors (Pillot, 2017). To date, the market share of electric and hybrid electric vehicles has been small, in 2019 3 % of new passenger car registrations in the EU were battery electric vehicles and plug-in hybrid electric vehicles, while 5.9 % were hybrid electric vehicles (ACEA, 2019). Nonetheless, the uptake of EVs has been rapid with sales on new electric vehicles exceeding 1 million globally in 2017 (IAE, 2018). It has been estimated that electric vehicles will make up the majority of new car sales worldwide by 2040, increasing to more than 60 million annually. (Bloomberg, 2018). Lithium-ion batteries have dominated the market and are anticipated also to do so in stationary energy storage applications in the near future. A significant growth is expected in the whole stationary battery market, as global battery storage capacity in stationary applications is forecast to rise from 11 gigawatt hours (GWh) in 2017 to 100–170 GWh by 2030 (Frost and Sullivan, 2018a; Global Market Insights, 2018; Tsiropoulos et al., 2018). Although the estimates for future lithium-ion battery market volumes and growth rates vary considerably, the demand for them for use in electric vehicles and stationary storage sectors in the next two decades is expected to grow rapidly. The past development and the future perspectives on the global lithium-ion battery market and different end-use sectors are presented in Table 4.1.

Table 4.1 Global lithium-ion battery market, gigawatt hours per year

	2010	2015	2020	2025	2030
Portable electronics	21	31	45	66	100
Road-transport	0	13	76	137	245
Storage in power supply	0	0	2	10	30
Other applications	1	1	2	7	15
Total	22	45	125	220	390

Source: Zubi et al. 2018

4.1 Critical raw materials in applications

This report mainly covers lithium ion batteries due to the expected increase in demand as well as their use of several critical raw materials. The critical raw materials used in these batteries are cobalt, natural graphite and to some extent, silicon. Historically, nickel metal hydride batteries have been the primary choice for hybrid electric vehicles, but these have some drawbacks when compared to lithium ion batteries, such as lower energy density and memory effect, and are thus being replaced by lithium ion batteries in both electric vehicles and consumer electronics (Hill et al, 2019). Currently, most electric vehicle manufacturers have shifted to lithium ion batteries, with the exception of Toyota who are still using nickel metal hydride batteries in some of their hybrid models ([16]). Nickel metal hydride batteries include several rare-earth elements – cerium, lanthanum, neodymium and praseodymium (Yao et al., 2018; Lebedeva et al., 2016).

[16] https://www.greencarreports.com/news/1120320_lithium-ion-vs-nickel-metal-hydride-toyota-still-likes-both-for-its-hybrids

Several possible cathode materials exist for lithium-ion batteries of which the most used are complex transition metal oxides and phosphates. These include lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), lithium manganese oxide (LMO) and lithium iron phosphate (LFP) (Lebedeva et al., 2016). These cathode materials and their main application are summarised in Table 4.2. Lithium cobalt oxide ($LiCoO_2$) is mainly used in small portable electronics such as smartphones and tablets, whereas lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminium oxide and their combinations with lithium manganese oxide are the most important cathode materials for electric vehicles. The demand for lithium iron phosphate is driven especially by the electric vehicle and e-bus market in China. In addition, it can be used for stationary energy storage where high energy density is not the main requirement.

The cobalt content in lithium nickel manganese cobalt oxide varies, state-of-the-art compositions being NMC111, NMC442 and NMC532, where the numbers denote the ratio of nickel, manganese and cobalt on a mole fraction basis. NMC622 and NMC811 are expected to enter the market in the near future (Cano et al, 2019). Nickel rich lithium nickel manganese cobalt oxide variants have the advantage of higher energy density and decreased amount of cobalt, a critical raw material, but at the expense of stability (Olivetti et al., 2017).

Table 4.2 Summary of main cathode materials, their applications and cobalt content

Cathode materials	**Main applications**	**Cobalt content required per chemistry in kg/kWh**
Lithium cobalt oxide (LCO)	Smart phones, tablets, other portable electronics	0.959
Lithium nickel manganese cobalt oxide (NMC)	Electric vehicles and other high-power applications, also electronics	NMC111: 0.394 NMC532: 0.230 NMC622: 0.214 NMC811: 0.111
Lithium nickel cobalt aluminium oxide (NCA)	Electric vehicles, power tools, electric bicycles, electronics	0.143 ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)
Lithium manganese oxide (LMO)	E Electric vehicles (blended with NMC/NCA), power tools	0
Lithium iron phosphate (LFP)	Electric vehicles, e-buses (especially in China), stationary storage	0

Source: Applications: Tsiropoulos et al. (2018); Pillot (2017); Cobalt content: Alves Dias et al. (2018); Olivetti et al. (2017)

For anode materials, the most important by far are graphite based materials with lithium titanate (LTO, $Li_4Ti_5O_{12}$) and silicon composites having only a minor market share (Shen et al., 2018). To date, natural graphite has been the most used anode material, but synthetic graphite is expected to increase its market share due to the requirement of higher purity in electric vehicle applications (Pillot, 2017). The use of silicon as anode material is expected to increase in the future due to its superior energy density. Mechanical degradation, caused by the large volume changes during use, has hindered the large-scale use of silicon in lithium ion battery anodes. Currently, some battery manufacturers add small amounts, less than 5 % by weight, of Si or SiO, in graphite electrodes (Placke et al., 2018).

Market shares of different cathode and anode materials used in lithium ion batteries in 2016 are shown in Figure 4-1.

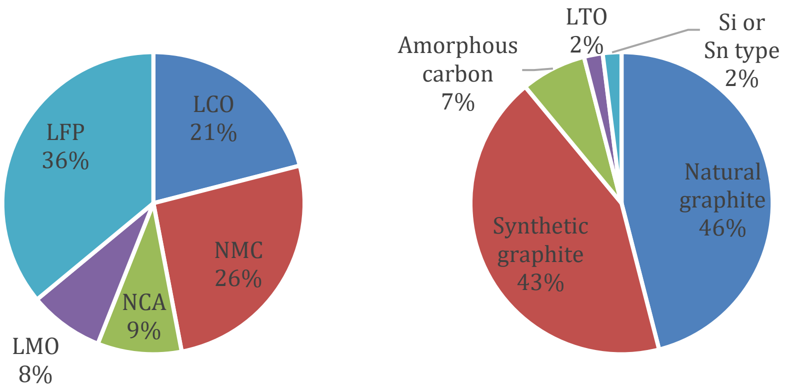

Figure 4-1. Market shares of cathode (left) and anode materials (right) used in lithium ion batteries, 2016, per cent by weight. LCO: lithium cobalt oxide, NMC: lithium nickel manganese cobalt oxide, NCA: lithium nickel cobalt aluminium oxide, LMO: lithium manganese oxide, LFP: lithium iron phosphate, LTO: lithium titanate, Si: silicon, Sn: tin.

Source: Pillot (2017)

In addition to active electrode materials, other components in lithium ion battery cells include materials manufactured using critical raw materials. For example, polyvinylidene fluoride (PVDF) is used as a binder in the electrodes, mainly in cathodes, and lithium hexafluorophosphate ($LiPF_6$) is used as a lithium conducting salt in the liquid electrolytes. Raw materials for these chemicals include critical raw materials -fluorspar and phosphate rock- but these are not discussed further in this report.

Nickel metal hydride (NiMH) batteries include several critical raw materials; most importantly rare-earth elements are used in anode alloys because of their hydrogen storage properties. The most commonly used rare-earth elements are cerium, lanthanum, neodymium and praseodymium (European Commission, 2017b). Rare-earth element content in nickel metal hydride battery cells is close to 10 % by weight, the majority of which is lanthanum (Tunsu et al., 2015; Larsson et al., 2013).

The negative electrode in a nickel metal hydride battery is a hydrogen-storing metal alloy, and several possible compositions exist such as AB_5 or AB_2 types. AB_5 is the most common type today, where the A-side element is a mixture of cerium, lanthanum, neodymium and praseodymium, and the B-side element is typically cobalt, nickel, magnesium and/or aluminium. The content and ratio of the rare earths, cerium, lanthanum, neodymium and praseodymium, are important factors in determining the performance and hydrogen storage capability of the anode. AB_2 type of alloys are intermetallic compounds where A is typically zirconium or titanium, and B is typically chromium, magnesium or vanadium (Ma et al., 2012).

The positive electrode in a nickel metal hydride battery is nickel oxyhydroxide NiO(OH). Additives, such as cobalt and zinc, are used in nickel hydroxide cathodes to enhance the performance. For example, an addition of cobalt enhances the reaction reversibility and improves mass transfer and electrical conductivity (Ma et al., 2012).

4.2 Economic importance and future aspects

4.2.1 Economic importance

In this report, the economic importance, reflects how critical raw materials used in the application generate economic importance to the European economy, based on the European Commission's 2017 assessment of critical raw materials. The distribution of economic importance of critical raw materials used in batteries is presented in Figure 4-2. It describes the share of the application in the economic importance of these particular critical raw materials.

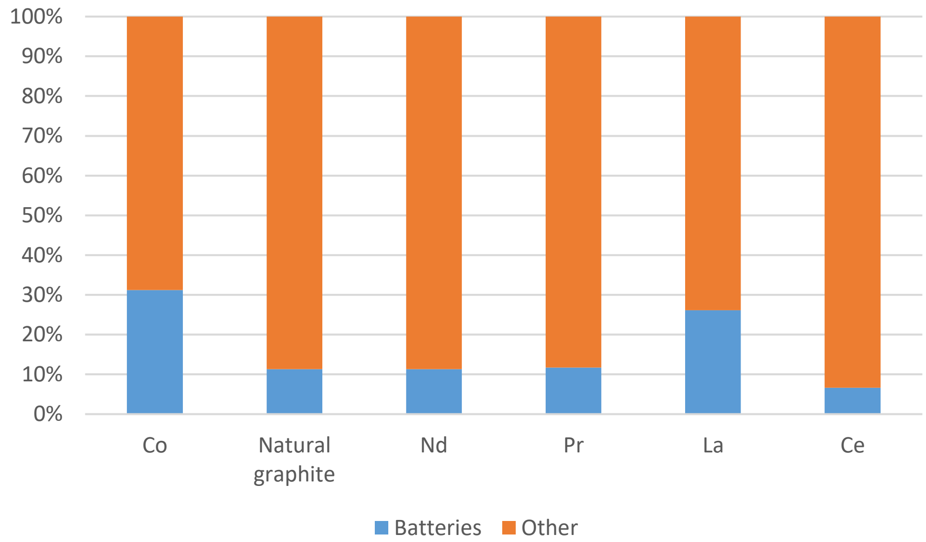

Figure 4-2 The contribution of batteries to the economic importance of critical raw materials, 2017, per cent

Source: ETC/WMGE based on European Commission (2017b)

Figure 4-2 shows that the contribution of batteries to economic importance was less than 30 % for any of the critical raw materials used. Batteries have highest economic importance for cobalt with a share of around 30 % followed by lanthanum with 26 % share, whereas for other critical raw materials the shares are below 10 %. The shares are perhaps not as high as expected, but it should be noted that an increase in battery demand occurred after 2017, and it is expected to increase considerably due, for example, to the electrification of transport.

The main increase in battery consumption is expected from the transport sector compared to, for example, consumer electronics which have previously dominated the battery consumption (Tsiropoulos et al., 2018). This will also affect raw material demand since consumer electronics commonly utilise lithium-cobalt-oxide batteries whereas electric vehicles increasingly use nickel-manganese-cobalt and nickel-cobalt-aluminium batteries which have a lower cobalt content (Tsiropoulos et al., 2018; Blagoeva et al., 2016). The market shares of electric vehicles, both plug-in hybrids and battery electric vehicles, have increased in Europe from slightly below 1 % of the total market in 2015 to roughly 3.3 % in 2019 (Statista, 2020a) and the share is expected to increase in the coming years.

The leading electric vehicle models in Europe in 2019 were the Tesla Model 3, the Renault Zoe and Mitsubishi's Outlander plug-in hybrid selling respectively 95,170, 45,130 and 34,600 units (Statista, 2020a).

4.2.2 Future aspects

The demand for batteries is expected to increase as electric vehicles enter the vehicle fleet in order to reduce the emissions from transport. According to Statista, 16.5 million electric vehicles will be produced in Europe in 2030 (Statista, 2020b). In 2030 share of the new car registrations for battery electric vehicles are expected to be between 3.9 % and 13.0 % and between 6.7 % and 22.1 % for plug-in hybrids, a significant increase compared to the 1.5 % for battery electric and plug-in-hybrid vehicles in 2017 (EEA, 2018).

The demand of cobalt in 2030 has been predicted to increase 23.8 times on 2015 levels of 510 tonnes due to the electrification of transport (EC, 2018). The EU's resilience to supply bottlenecks of cobalt will continue to deteriorate in the coming decade unless substitution and recycling measures increase by 2030 (Blagoeva et al., 2016). Additionally, the demand for graphite is expected to be 25.8 times 2015 levels of 8,340 tonnes by 2030 (EC, 2018). Substitution has been identified as an effective mitigation strategy for graphite. In addition, the potential increase in the EU's domestic production and recycling also play important roles (Blagoeva et al., 2016). For graphite it should be noted that artificial graphite can be used instead of natural graphite, which may affect the demand situation (Karhu et al., 2019).

4.3 Environmental aspects

4.3.1 Risks and impacts critical raw materials in applications

The main critical raw materials used in batteries are cobalt, natural graphite and silicon in lithium ion batteries, and cerium, lanthanum, neodymium and praseodymium in nickel metal hydride batteries (Yao et al., 2018; Lebedeva et al., 2016). The environmental hazard potential of these critical raw materials is shown in Table 4.3. Cobalt and rare-earth element extraction and production have medium and high environmental hazard potentials for most indicators, while natural graphite has a low risk for most indicators.

Table 4.3 Evaluation of the environmental hazard potential of critical raw materials in batteries ([17])

	Goal	Indicator	Cobalt	Natural graphite	Rare-earth elements
			Katanga, DRC	Heilongjiang Province, China	Bayan Obo, China
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element, mostly oxidised with sulphides in some sections	Graphite is not usually available as a sulphide	Lithophylic elements
		Paragenesis with heavy metals	Cobalt is associated with copper	Graphite is an abiotic non-metallic raw material	Soil in the mining area of Bayan Obo has been found to be contaminated with cadmium, chromium, copper, lead and zinc
		Paragenesis with radioactive components	No information found on levels of uranium and thorium in Mutanda, however, radioactive elements are present in other cobalt deposits in the DRC	Graphite is not available in paragenesis with radioactive components	0.16 % thorium oxide, also uranium
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Graphite is mined in underground mining. Since the deposits usually are lode deposits, they require selective extraction	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Extraction involves acid	Graphite is usually processed using flotation and auxiliary chemicals	Extractants such as D2EHPA, TBP, and aliquat 336 have been widely used ([18])
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquake, storms, landslides	DRC: low natural accident hazard	China: high natural accident hazard	China: high natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	Low water stress	Low water stress

[17] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.
[18] D2EHPA, di-(2-ethylhexyl)phosphoric acid; TBP, tributyl phosphate; aliquat 336, N-Methyl-N,N,N-trioctylammonium chloride

	Goal	Indicator	Cobalt	Natural graphite	Rare-earth elements
			Katanga, DRC	Heilongjiang Province, China	Bayan Obo, China
	Protection of valuable ecosystems	Protected areas and AZE sites	Very close to Marungu Highlands AZE site	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	DRC: low EPI	China: medium EPI	China: medium EPI
Value chain	Carbon footprint (kton CO_2-eq/application)		4.7E+02	2.1E+00	1.4E+02
	Cumulative Energy Demand (TJ/application)		7.3E+03	4.0E+01	2.8E+03
	Human toxicity, cancer and non-cancer (CTUh/application)		2.2E+02	6.9E-01	6.8E+01
	Terrestrial acidification (kton SO_2-eq/application)		5.1E+00	1.0E-02	6.2E-01
	Freshwater eutrophication (kton P-eq/application)		2.3E-01	1.4E-03	5.6E-02

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([19]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([20]), AZE sites: 2018 - 2020 American Bird Conservancy ([21]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), cobalt: Golder Associates, 2011; Shengo, 2018, Mindat.org ([22]), Glencore ([23]), natural graphite: Dehoust et al., 2017, rare-earth elements: Ferro and Saccone, 2008; Koltun and Tharumarajah, 2010; Xie et al., 2014; Pan and Li, 2016; Liu et al., 2018

More information on the environmental impacts of cobalt and rare-earth elements can be found in Section 3.3.1.

Graphite mining, most of which takes place in in China, has led to many environmental problems there, such as groundwater and soil contamination, and air pollution (Q. Yang et al., 2017). In 2013, the Chinese government suspended 55 graphite mining operations due to environmental concerns and the potential health risk of airborne graphite dust (Laurent, Espinosa and Hauschild, 2018). A life cycle assessment on natural graphite for anodes showed that the highest environmental impact was due to the consumption of electricity for purification and surface modification, due to the Chinese electricity mix which heavily relies on coal (Zhang et al., 2018).

4.3.2 Impact of applications from a lifecycle perspective

The lifecycle stages that contribute most to the environmental impact of any battery are the extraction and refining of electrode materials (Science for Environment Policy, 2018). Lithium ion batteries commonly contain cobalt in the cathode, together with other metals including lithium, nickel,

[19] https://risk.preventionweb.net/
[20] https://www.protectedplanet.net/
[21] https://zeroextinction.org/site-identification/2018-global-aze-map/
[22] https://www.mindat.org/loc-294223.html
[23] https://www.glencore.com/dam/jcr:851138e1-268a-4554-ad03-c6b8dea21308/Glencore-Sell-Side-Analyst-Visit-Mutanda-201311.pdf

manganese and aluminium. Cathodes with large amounts of cobalt and nickel require the greatest energy for their production (Dunn et al., 2016).

Dai et al. (2019) analysed the cradle-to-gate lifecycle of the industrial production of lithium nickel manganese cobalt oxide batteries, more specifically NMC111, as they are the predominant in electrical vehicles currently sold in Europe, Japan and the United States. Their analysis shows that the active cathode material, aluminium and energy use for cell production cause the batteries' main environmental. The cobalt sulphate ($CoSO_4$) used to produce the cathode accounts for approximately 9 % of the energy use, 9 % of the greenhouse gas emissions, 6 % of the sulphur oxide emissions, 11 % of the nitrogen oxide emissions, 48 % of the PM_{10} ([24]) emissions and 17 % of the water consumption of the complete battery production (Dai et al., 2019). Most life cycle assessments found assume that synthetic graphite was used, and its contribution to a battery's impact is limited. As natural graphite is likely to have lower impacts on human health, ecosystems and climate than synthetic graphite (Ellingsen et al., 2018), its contribution to total battery impacts is likely to be small. Dai et al. (2019) note that the environmental impacts of a battery depend on the region from which the materials are sourced and where the battery is produced.

The critical raw materials, especially cobalt, make a relevant contribution to the environmental impact of the batteries. When looking at the total environmental impact of the end use application, however, it is relatively limited. The production of a lithium nickel manganese cobalt oxide battery, for example, accounts for a maximum 25 % of the lifecycle greenhouse gas emissions of an electric vehicle (Dunn et al., 2015). This is, however, in a pioneer, low throughput battery production plant. The environmental impact of an electric vehicle is largely due to the electricity use during its operation – the heavier the battery, the higher the electricity consumption. It is thus very important for applications in electric vehicles to achieve a high energy density (Science for Environment Policy, 2018). Figure 4-3 shows that the contribution of the critical raw materials in the battery to the total climate change impact of an electrical vehicle is small.

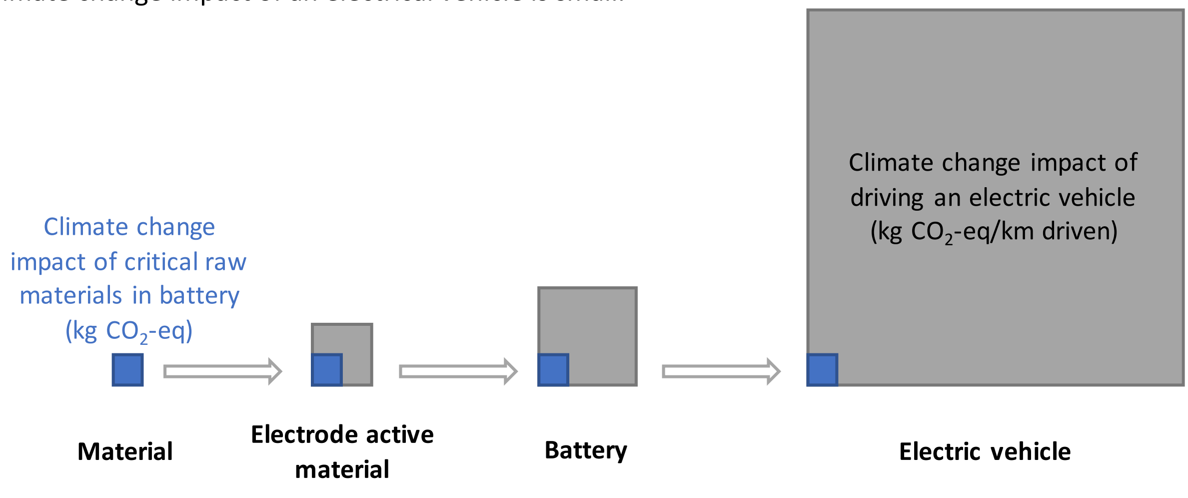

Figure 4-3 The contribution of critical raw materials in a battery to the impact on climate change in an EV ([25])
Source: based on Dai et al. (2019) and Dunn et al. (2016)

[24] Particulates with a diameter of less than 10 micrometres
[25] The first block shows the greenhouse gases emitted due to the production of the critical raw materials needed to deliver the final function, driving an electric vehicle. In the next lifecycle stages of the lifecycle, the greenhouse gases that are related to other materials, energy use, direct emissions and waste are added. Data on greenhouse gas emissions were obtained from Dai et al. (2019) and Dunn et al. (2016). The calculations are based on an NMC battery, a high-throughput battery plant, and California's electricity grid. The share of critical raw materials in the battery in the total climate change impact of driving an electric vehicle is about 1 %.

Batteries are often used to reduce climate impact and, indeed, they can help achieve a greater use of renewable energy (Science for Environment Policy, 2018). Their use in electric and hybrid electric vehicles can facilitate the transition to transport with a lower carbon footprint.

4.4 Substitution solutions

4.4.1 Graphite and cobalt-free lithium ion chemistries

Substitution of critical raw materials is not the only driver for seeking alternative materials for lithium ion batteries; insufficient capacity, high cost, and safety of current commercial electrode materials also act as drivers for their replacement (Shen et al., 2018). Moreover, safety issues caused by the use of flammable organic electrolytes in conventional lithium ion batteries have also accelerated the development of alternatives (Zhao et al., 2019). As a result, there are many material options for both anode and cathode sides of lithium ion batteries, enabling various battery designs. However, the current material combinations almost exclusively employ critical raw materials on at least one electrode.

Graphite-free anodes

When high power is needed, lithium titanate ($Li_4Ti_5O_{12}$) can be used as the anode material. Another possible substitution solution for graphite is the use of tin-based oxides (SnO and SnO_2). Particularly promising results for high-power applications have been achieved by the combination of tin oxides with various carbon nanostructures (Shen *et al.*, 2018; Saxman, 2016). Commercial examples of tin-based anode materials exist in portable applications (Saxman, 2016).

Silicon has been considered as one of the most attractive anode materials for lithium ion batteries because it has the highest gravimetric capacity among anodes. It should, however, be noted that silicon metal is a critical raw material for the EU, although generally silicon is considered abundant (Shen et al., 2018; European Commission, 2017b). The drawback of silicon-based anodes is currently the capacity fading occurring during the discharge-charge process. To overcome this issue, many approaches have been applied to develop novel silicon electrodes with high electrochemical performance, such as by designing the morphology of silicon on a nanoscale or by surface coating (Shen et al., 2018; Saxman, 2016). The use of silicon or carbon-silicon anodes is expected to characterise future generation battery designs (Frost and Sullivan, 2017a; Lebedeva et al., 2016).

Cobalt-free cathodes

One of the most promising lithium ion battery cathode materials is lithium iron phosphate ($LiFePO_4$), as a substitute to lithium cobalt oxide (Saxman, 2016), especially for large-scale lithium ion batteries, such as those used in electric and hybrid vehicles and stationary energy storage. The substitutive material combination is based on low cost and abundant raw materials. The drawback of the material is its very low electronic conductivity at room temperature, and lower energy density when compared to cobalt oxide based cathode materials. Various approaches to improve the poor conductivity have been developed, such as coating lithium iron phosphate with different conducting materials (Shen et al., 2018). Several companies have commercialised lithium ion batteries based on lithium iron phosphate cathodes (Saxman, 2016), thus the solution is already on the market.

Li_5FeO_4, has also been successful at a laboratory scale as a replacement of cobalt by a lithium-rich cathode design. The design is advantageous not only because of cobalt substitution, but because the capacity of the cell is significantly higher (Frost and Sullivan, 2018b; Zhan et al., 2017).

Solid-state lithium ion chemistry

Solid-state batteries employ solid electrolytes in contrast to liquid electrolyte batteries, such as conventional lithium ion batteries. Solid-state batteries are seen as less hazardous, less flammable and having a better storage capacity. As a result they are used to power, for instance, cardiac pacemakers. However, solid-state batteries are not suitable for use at less than room temperature because of the large resistance of the solid electrolyte to ionic conductivity at low temperatures. Moreover, the power and current output of solid-state batteries is generally less than in liquid electrolyte batteries (Kim et al., 2015).

Figure 4-3 is a schematic representation of a lithium-based solid-state battery with corresponding anode, electrolyte and cathode material combinations, as indicated by matching colours for each component of the battery. Many cobalt- and graphite-free alternatives exist for electrode materials, but other critical raw materials, namely vanadium and indium, are employed in several alternatives.

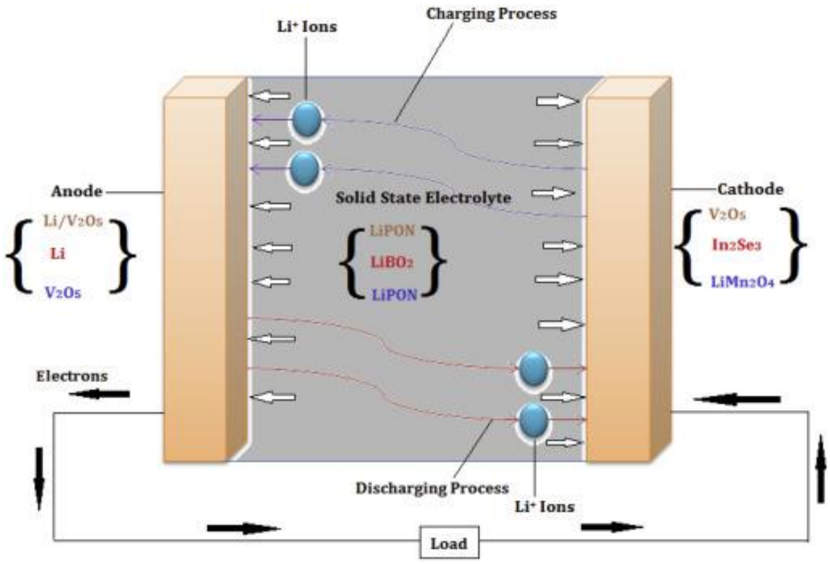

Figure 4-3 A schematic representation of a lithium-based solid-state battery with some of the possible anode, electrolyte, and cathode combinations

Source: Kim et al. (2015)

4.4.2 Alternatives for Li-ion chemistries

It has been assumed that in the short term, sodium-ion and lithium-sulphur battery technologies are the best candidates to reach sufficient technology maturity to allow wider commercial deployment and substitution of lithium ion batteries (Frost and Sullivan, 2017b).

Sodium ion batteries

Compared to lithium, sodium (Na) has similar physical and chemical properties, but it is very abundant and cheap compared to lithium. However, the gravimetric and volumetric densities of a sodium ion (Na-ion) battery cannot exceed those of its lithium analogue because of the relatively heavier and larger sodium atom and sodium's smaller reduction potential. On the other hand, as energy density is not a critical issue for stationary energy storage systems, developing room-temperature sodium ion batteries for this application is still considered a reasonable alternative (Pan, Hu and Chen, 2013).

The commercialisation of sodium ion technology has already reached an early stage for stationary grid storage (Frost and Sullivan, 2017b). However, the electrode materials for sodium ion batteries are yet to be established and there are number of materials are under development. On the cathode side, layered transition metal oxides, tunnel-type oxides and phosphates are being considered, while on the anode side, carbon-based compounds, oxides and sulphides, to name a few, have been examined. Some of these alternatives employ cobalt (Pan et al., 2013).

Lithium sulphur batteries
Due to the abundance and low cost of elemental sulphur, a lithium sulphur batteries are considered as an advantageous alternatives to lithium ion systems. In these batteries, lithium forms the anode, whereas sulphur and carbon are used on the cathode side. Lithium sulphur batteries are expected to deliver 3–5 fold higher specific capacity and energy density than lithium ion ones (Zhang, 2013).

Key applications of lithium sulphur batteries are transportation, military and defence, and stationary grid batteries. Current market for these batteries is in the pilot stage and it is estimated that they will be commercially available after 2030 (Frost and Sullivan, 2017b).

Lithium air batteries
Lithium air systems, more precisely lithium-oxygen systems, are the most promising lithium batteries in terms of energy density, since the cathode active mass is not included in the battery system. These batteries have the potential to produce more than an order of magnitude higher energy density than lithium ion batteries. As a result, lithium air batteries are considered to be competitive even with liquid fuels (Shen et al., 2018). As with lithium sulphur batteries, lithium air batteries are expected to be commercially available after 2030 (Frostand Sullivan, 2017b).

There are two types of lithium air batteries: aqueous and non-aqueous, and both types involve the reduction of molecular oxygen (O_2). Both types also face many challenges for practical implementation. In a non-aqueous lithium air battery, the solid lithium peroxide (Li_2O_2) accumulates in the porous cathode substrate on discharge. Various catalysts have been tested in order to reduce the voltage separation in this battery type, some of which employ cobalt. There are, however, a number of potential critical raw material free catalysts available, such as those based on manganese oxides (Shen et al., 2018).

Redox flow batteries
Redox flow batteries (RFBs) employ two soluble redox couples retained in external electrolyte tanks, sized according to the application's requirements. Instead of storing energy in electrode materials, it is stored in the form of the dissolved redox couples in the electrolyte (Wang et al., 2013).

This is considered to be one of the most promising technologies for stationary energy storage because of the features it provides, such as, the ability to store multi megawatts (MWs) and megawatt-hours (MWh) of power and energy; the ability to control power and energy capacities separately from each other; and safety in operation. Several different forms of redox flow batteries exist, some using critical raw materials, the most common of which include redox couples based on iron/chromium, vanadium/ vanadium, polysulphide/bromine, zinc/bromine and vanadium/cerium (Wang et al., 2013).

4.4.3 Alternatives to batteries

With the transition towards greater use of renewable energy, hydrogen is often considered a very capable future energy-storage and energy-transport medium as it can be produced with renewable energy by electrolysis. As a result of the limitations related to the storage of hydrogen and the considerable investment costs involved in establishing a distribution infrastructure for hydrogen, research is focusing on ways of storing and transporting it in chemically bound forms, referred to as energy carrying compounds (Teichmann et al., 2012).

Some examples of energy carrying compounds are liquid organic hydrogen carriers (LOHCs), where hydrogen is covalently bound to a liquid carrier substance by hydrogenation. When needed, the hydrogen can be released by dehydrogenation (Niermann et al., 2019). The storage medium itself is not consumed but can be reloaded with hydrogen in further cycles (Teichmann et al., 2012). Liquid organic hydrogen carrier technology is used in a number of ways in the long-distance transport of energy or for stationary energy storage. It could also be used to store energy for hydrogen-powered fuel cell vehicles, in the way that batteries are used for storing energy in electric vehicles (Aakko-Saksa et al., 2018). Various substances have been studied as potential hydrogen carrier media – heterocyclic aromatic hydrocarbons are among the best-understood (Teichmann et al., 2012).

4.4.4 Secondary raw materials

Recycling technologies for lithium ion batteries have not been able to keep pace with their production. Collection and recycling rates of batteries from portable devices at the end of their lives are rather low, whereas batteries from electric vehicles are only starting to reach end of their lives on a large scale. The existing industrial recycling processes are only capable of recovering materials that require further processing before they can be used in new batteries. Moreover, most recycling technologies require high concentrations of cobalt in order to be profitable, and necessitate rigorous sorting of batteries prior to processing (Heelan et al., 2016).

The main recycling methods can be divided into pyrometallurgical, hydrometallurgical and direct recycling methods. In pyrometallurgical recycling, high-temperature furnaces are used to reduce the metal oxides to an alloy of cobalt, copper, iron and nickel. Other products of the pyrometallurgical process are slag, containing aluminium, lithium and manganese, and gases. Hydrometallurgical processes are based on using aqueous solutions, most often sulphuric acid (H_2SO_4)/hydrogen peroxide (H_2O_2), to leach the desired metals from cathode material. In direct recycling, cathode or anode materials are removed from the electrode for reconditioning and re-use in new lithium ion batteries. The reincorporation of metal oxide cathode materials in new cathodes will often require the replenishment of the lithium content (Harper *et al.*, 2019). Table 4.4 presents a comparison of the main attributes of pyrometallurgical, hydrometallurgical and direct recycling.

Table 4.4 Comparison of recycling methods for lithium ion batteries. The colour scale indicates options from best (green) to worst (red) based on different criteria.

	Technology readiness	Quality of recovered material	Quantity of recovered material	Energy use	Production cost	Recovered elements
Pyrometallurgy	High	Low	Medium	High	Low	Co, Ni, Cu (Mn)
Hydrometallurgy	Medium high	Medium	Medium high	Medium	Medium	Co, Ni, Cu, (Mn), Al, (Li)
Direct recycling	Medium low	Medium low	High	Medium	High	Co, Ni, Cu, Mn, Al, Li

Source: Harper et al. (2019)

4.4.5 Environmental impacts

Even though many alternatives for batteries containing critical raw materials are being developed, the main driver behind battery research and development is not the environmental impact, but cost and performance targets (Dühnen et al., 2020). The reason for avoiding cobalt, the critical raw material with the highest environmental impact in batteries, is cost, though moral and environmental concerns on questionable mining conditions in central Africa also play a key role (Dühnen et al., 2020).

Natural graphite, an anode material, has few environmental risks and relatively low environmental impacts in the value chain (Table 4.3). The possible substitutes, lithium titanate, tin-based oxides and silicon, have greater environment risks (Table 4.5). From an environmental perspective, it would only be beneficial to replace graphite with these materials if environmental gains can be achieved in the rest of the lifecycle – for example, by improving performance – that outweigh the higher impact of mining and processing.

The cobalt used in cathodes has a medium to high environmental hazard potential for most indicators, and relevant environmental impacts throughout the value chain (Table 4.3). However, replacing lithium cobalt oxide by lithium iron phosphate may not substantially reduce the environmental risks, since phosphate also has a medium to high environmental hazard potential for most indicators. Additionally, lithium iron phosphate cathodes have lower energy density, which may result in higher overall impacts of the application. Replacement of cobalt by a lithium-rich cathode could reduce the environmental risks associated with raw material production, as lithium mining and processing creates fewer risks compared to cobalt.

It is much more difficult to evaluate the environmental effects of alternative battery chemistry and alternative energy storage systems. A complete lifecycle assessment at the application level should be done, taking into account the impacts in all lifecycle phases. As the contribution of the critical raw materials to the environmental impact of the end application is relatively limited, the outcome will mainly depend on other factors than their amount used, such as the energy density of the battery.

Table 4.5 Evaluation of the environmental hazard potential of substitutes for critical raw materials in batteries ([26])

	Goal	Indicator	Tin	Silicon	Lithium	Titanium	Phosphate
			Gejiu, China	Jiangsu, China	Bridgetown-Greenbushes, Australia	Hainan, China	Kaiyang, China
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element in granite, no sulfidic minerals	Lithophylic element	Lithophylic element in pegmatite	Lithophylic element	Siderophilic element, association can contain sulfides, not clear if this is the case for this deposit
		Paragenesis with heavy metals	Groundwater in the mining area has been found to be contaminated with As and other heavy metals	No indications that silicon is associated with heavy metals	Ore has elevated metal concentrations, especially arsenic and lithium	Titanium may be associated with chromium	Arsenic, chromium, lead, mercury, nickel and cadmium are frequently associated with phosphate rock
		Paragenesis with radioactive components	No indications that tin is associated with elevated levels of uranium and thorium	No indications that silicon is associated with elevated levels of uranium and thorium	No indications that lithium is associated with elevated levels of uranium and thorium	No indications that titanium is associated with elevated levels of uranium and thorium	High radioactivity has been found in a sample of Kaiyang
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit and underground	Open pit	Open pit and underground	Unconsolidated sediment mining	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Leaching with acid can be done to remove impurities	Produced in electric arc furnace	Predominantly gravity processing methods, acid washing step for chemical grade lithium	Mainly gravity, magnetic and electrostatic separation	Processing with acid

[26] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

	Goal	Indicator	Tin	Silicon	Lithium	Titanium	Phosphate
			Gejiu, China	Jiangsu, China	Bridgetown-Greenbushes, Australia	Hainan, China	Kaiyang, China
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	China: high natural accident hazard	Australia: medium natural accident hazard	China: high natural accident hazard	China: high natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	High water stress	Low water stress	Low water stress	Low water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	Very close to AZE site Hong He valley	No relation to protected areas or AZE sites	Various forest conservation areas in the surroundings	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium EPI	China: medium EPI	Australia: high EPI	China: medium EPI	China: medium EPI

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([27]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([28]), AZE sites: 2018 - 2020 American Bird Conservancy ([29]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), tin: Yanbo and Jingwen, 2010; Cheng et al., 2016, Applied Mineral Exploration ([30]), General Kinematics Corporation ([31]), silicon: Ferro and Saccone, 2008; Boussaa et al., 2016, WorldAtlas ([32]), lithium: Ferro and Saccone, 2008; Talison Lithium Australia, 2018, British Geological

[27] https://risk.preventionweb.net/
[28] https://www.protectedplanet.net/
[29] https://zeroextinction.org/site-identification/2018-global-aze-map/
[30] https://www.appliedminex.com/decrep/china/kunming/gejiu.htm
[31] https://www.generalkinematics.com/blog/tin-mining-processing-everything-need-know/#:~:text=Spain%20and%20Japan.-,Tin%20Mining%20Process,remove%20any%20heavy%20metal%20impurities.
[32] https://www.worldatlas.com/articles/top-15-quartz-exporting-countries.html

Survey ([33]), titanium: Ferro and Saccone, 2008; Dehoust et al., 2017, U.S. Geological Survey ([34]), KYOCERA SGS Precision Tools Europe ([35]), phosphate: Ferro and Saccone, 2008; International Atomic Energy Agency, 2015; Reta et al., 2018, U.S. Geological Survey ([36])

33 https://www.bgs.ac.uk/downloads/start.cfm?id=3100
34 https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10231339
35 https://kyocera-sgstool.co.uk/titanium-resources/titanium-information-everything-you-need-to-know/titanium-ores/
36 https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10239757

Secondary raw materials

Using secondary critical raw materials to produce batteries can result in significant environmental savings. Producing lithium cobalt oxide cathodes from (pyrometallurgically) recycled materials could reduce greenhouse gas emissions by up to 75 % compared to production from virgin raw materials (Dunn et al., 2015). Furthermore, the sulphur oxide emissions of recycled lithium cobalt oxide production are negligible compared to its virgin production, due to the avoidance of the sulphur oxide -intensive smelting step needed for virgin cobalt production (Dunn et al., 2015).

5 Alloys

Different types of alloys containing critical raw materials are used in numerous applications. In this report, the analysis of alloys focuses on alloys used in cars due to the wide array of alloys used in different applications, which would have made the analysis overly extensive.

In a typical car, 75 % of the weight consists of base metals such as iron and steel, aluminium and copper, and 60 % of the total weight is in the vehicle body and chassis components (Mallick, 2012). It has been estimated that a weight reduction of 10 % in a typical car could reduce the fuel consumption by 3–7 % (Modaresi et al., 2014). As a result, carbon steel is increasingly replaced with high strength steels and light non-ferrous alloys such as aluminium alloys (Mallick, 2012). Critical raw materials are applied as alloying elements in many of these advanced materials.

High strength steels are increasingly used in vehicle body and chassis structures due to their strength and reduced weight. These include, for example, high-strength low alloy (HSLA) steels and advanced high-strength steels (AHSS) (Mallick, 2012). The properties of the high-strength low alloy and advanced high-strength steels originate from the alloying elements creating a complex microstructure with the base metal (Karhu et al., 2019; Mallick, 2012).

Cast and wrought aluminium alloys are used in cars to reduce the weight, such as in the engine, transmission and suspension components as well as in body structure and panels (Mallick, 2012). Aluminium alloys can be classified according to the alloying element and composition. The most extensively used aluminium alloys in cars are the non-heat-treatable aluminium-magnesium (5,000 series) and the heat-treatable aluminium-magnesium-silicon (6,000 series) alloys (Salonitis et al., 2009).

Other types of alloys containing critical raw materials are also present in cars though in lesser amounts. These include magnesium, stellite and copper-beryllium alloys.

5.1 Critical raw materials in applications

Various critical raw materials are used in different types of alloys in cars. The most important by volume are magnesium, used in aluminium alloys, and niobium and vanadium used in high-strength low alloy steels (Ortego et al., 2018; Field et al., 2017;). In addition, several other critical raw materials are used including silicon in aluminium alloys (Tercero et al., 2018), manganese and rare-earth elements in magnesium alloys (Tercero et al., 2018), cobalt and tungsten in stellite alloys (Karhu et al., 2019) and beryllium in copper-beryllium alloys (Tercero et al., 2015).

High strength and stainless steels

Niobium is used as an alloying element in high-strength low alloy and advanced high-strength steels, increasing their strength by affecting the microstructure of the alloy (European Commission, 2017b). Thus, lower weight materials are achievable due to strength increase. In addition, adding niobium results in increased resistance to corrosion and high temperatures (Tercero et al., 2018). The amount of niobium in high-strength low alloy steels is very low, 0.02–0.06 % by weight (Vervynckt et al., 2012).

In addition to high-strength low alloy and advanced high-strength steels, 3 % of niobium produced is used in the production of some stainless steel grades (Tercero et al., 2018). Stainless steel is used for example in car exhaust systems due to its excellent corrosion and oxidation resistance (Mallick, 2012).

Vanadium is another important additive in high-strength low alloy and advanced high-strength steels. Similar to niobium, vanadium increases strength and thus reduces the weight of the alloy. In addition, vanadium improves resistance to corrosion in high strength steels (Tercero et al., 2018).

In addition, natural graphite is used in steel manufacturing as refractory material due to its high durability, erosion resistance, thermal shock resistance and thermal conductivity (Tercero et al., 2018). In steel manufacturing, natural graphite is used in magnesia-carbon (MgO-C) bricks which are used, for example, as a lining material in furnaces. In foundries, natural graphite is used for foundry coatings to protect refractory linings, troughs and other foundry equipment (European Commission, 2017b).

Aluminium alloys

Magnesium is used in a variety of aluminium alloys to increase the strength and reduce weight. The most relevant ones for cars are 5,000, 6,000 and 7,000 series aluminium alloys. Magnesium is most relevant for the 5,000 series aluminium alloys in which magnesium accounts for up 6 % of the weight, and is essential for the 6,000 series in which the main alloying elements are magnesium and silicon, and the 7000 series for which the main alloying elements are zinc and magnesium (Tercero et al., 2015; Mallick, 2012). According to Field et al. (2017) vehicles contain approximately 3 kilograms of magnesium.

Silicon is used in different aluminium alloys the most relevant of which for cars are 6,000 series, aluminium-silicon-magnesium alloys. As with the above mentioned alloying elements, silicon reduces the weight of the aluminium alloy and in addition provides excellent casting properties (Tercero et al., 2018).

Magnesium alloys

In addition to aluminium alloys, magnesium is used in cast and wrought magnesium alloys (Tercero et al., 2018). Although they are light, the use of manganese alloys in the car industry is limited as these alloys are expensive and lack formability and corrosion resistance, (Kim, 2014).

Some heavy rare-earth elements can also be used in magnesium alloys, primarily yttrium. These elements increase corrosion resistance and the strength of manganese alloys at elevated temperatures (Binnemans et al., 2018; Tercero et al., 2018).

Cobalt alloys (stellite)

Cobalt alloys, such as stellites, are used in engine valves and valve seats for which excellent high-temperature resistance and corrosion performance are required. Other elements such as tungsten may also be included to increase wear resistance. (Karhu et al., 2019)

Copper alloys

Beryllium is used in copper-beryllium alloys to improve mechanical properties while retaining high electrical conductivity. Copper-beryllium alloys are used in electrical and electronic connectors in cars when high reliability is required, for example in air-bag crash sensors, anti-lock brake systems, traction control and all engine sensors (Tercero et al., 2015). These copper-beryllium alloys typically contain less than 2 % of beryllium (Trueman and Sabey, 2014).

Tungsten carbide

Tungsten carbides, and cemented carbides, are hard metals used mainly for cutting, drilling and wear-resistant parts or coatings due to their hardness and resistance to high temperatures and wear (Brown and Pitfield, 2014). In cars, tungsten carbide coatings are found primarily in valves and valve inserts, but also in engines, turbochargers, fuel pumps and cylinder inserts (Field et al., 2017).

5.2 Economic importance and future aspects

5.2.1 Economic importance

In the report, economic importance reflects how critical raw materials used in applications generate economic importance to the European economy, based on the European Commission's 2017 assessment of critical raw materials. The distribution of economic importance of critical raw materials used in metal alloys is shown in Figure 5-1. It describes the share of the application in the economic importance of these particular CRMs.

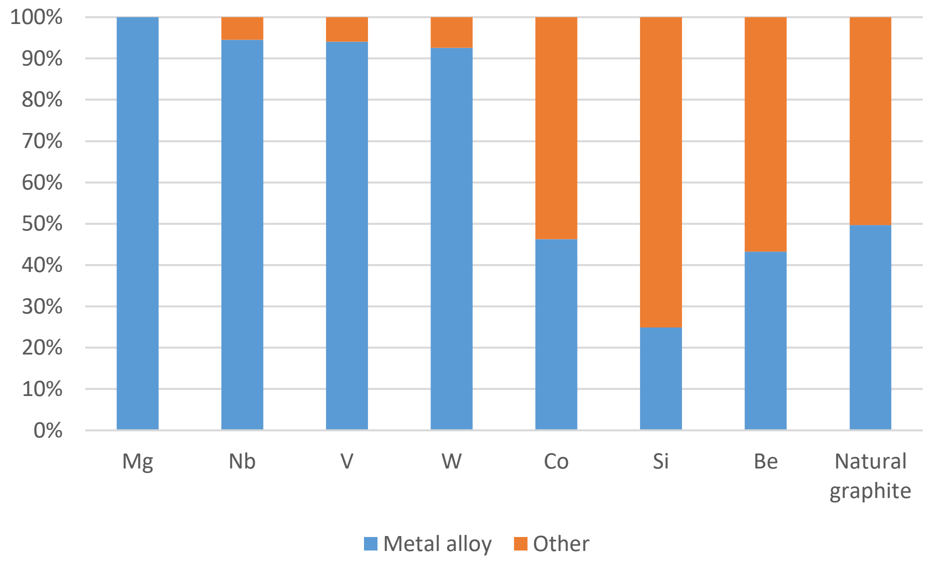

Figure 5-1. The contribution of metal alloys to the economic importance of critical raw materials, per cent

Source: ETC/WMGE based on European Commission (2017b)

For so-called refractory metals – magnesium, niobium, vanadium and tungsten – metal alloys make up more than 90 % of their economic importance. These metals provide special features for alloys such as heat and wear resistance as well as strength which are important, for example, to the transport industry. For cobalt and natural graphite, metal alloys generate slightly below 50 % of their economic importance. Natural graphite is used in the refractories in steel making so it is not directly linked to the alloy but in its manufacturing. For beryllium, copper-alloys in transport also generate slightly below 50 % of their economic importance, but if all different applications are taken into account including consumer electronics, their economic importance is more than 90 %. For silicon metal, the metal alloys generate around 25 % of its economic importance.

Overall, many of the critical raw materials used in metal alloys are linked to the markets and trends in the transport industry.

5.2.2 Future aspects

Beside electrification of the transport sector another essential activity in reducing environmental impacts in the use stage is making the vehicles lighter and therefore more fuel-efficient. It may be a welcome also for electric vehicles when increasing their range is desired. Magnesium is a relevant element when making lighter alloys and therefore its use in the car industry is expected to increase modestly (Tercero, 2019). A similar increase can be anticipated for niobium as it strengthens the high-strength low alloy steel, resulting in lighter structures. Nevertheless, the use of superalloys, which also contain niobium, might fall when electrical vehicles replace internal combustion ones (Tercero, 2019).

For beryllium, which is used in car electronics, the evolution of electronics in vehicles provides an indication of future demand, even though exact numbers are not available. In 2010, the cost of an electronic system in a vehicle represented 35 % of its total cost whereas by 2030 it estimated to rise to 50 % (Deloitte, 2019). Furthermore, Burkacky et al. (2019) predict that the global market of automotive components will grow by 7 % annually between 2020 and 2030.

5.3 Environmental aspects

5.3.1 Risks and impacts of critical raw materials in applications

Some of the most important critical raw materials used in alloys are magnesium, niobium, silicon tungsten and vanadium. The environmental hazard potential of these is shown in Table 5.1. All critical raw materials have medium to high environmental hazard potentials for at least eight indicators. Niobium and tungsten have a high pollution risk at the mining site, vanadium has a medium risk. Magnesium has a low pollution risk at the mining site, but in alloys it has a high impact on the value chain indicators, such as the carbon footprint. The reason for this is that a very large quantity of magnesium is used to produce alloys. Since magnesium, silicon and vanadium are mainly produced in China, they have high natural accident risk and a water stress risk depending on the region from which they are sourced. All these critical raw materials are generally produced in countries with medium score on the Environmental Performance Index, increasing the likelihood that all necessary measures to protect the environment are not taken.

Table 5.1 Evaluation of the environmental hazard potential of critical raw materials in alloys ([37])

	Goal	Indicator	Magnesium	Niobium	Vanadium	Silicon	Tungsten
			Pailou, China	Araxá, Brazil	Chengde, China	Jiangsu, China	Nui Phao, Viet Nam
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Lithophylic element	Lithophylic element	Lithophylic element	Lithophylic element	According to the Goldschmidt classification, tungsten is a siderophilic (sulphur-loving) element and available both as a sulphide and an oxide
		Paragenesis with heavy metals	No indications that magnesium is associated with heavy metals	Elevated levels of chromium, zinc, copper and lead found in sedimants close to mine	Magnetite deposits contain chromium	No indications that silicon is associated with heavy metals	Soil in the mining area of Nui Phao has been found to be contaminated with arsenic
		Paragenesis with radioactive components	No indications that magnesium is associated with elevated levels of uranium and thorium	Uranium and thorium present in pyrochlor	No indications that vanadium is associated with elevated levels of uranium and thorium	No indications that silicon is associated with elevated levels of uranium and thorium	No indications that tungsten is associated with elevated levels of uranium and thorium
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Open pit	Open pit and underground	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Thermal process	Flotation of pyrochlore, use of acids and other chemicals	By-product of iron production in blast furnace	Produced in electric arc furnace	Combination of flotation and gravity processes

[37] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

	Goal	Indicator	Magnesium	Niobium	Vanadium	Silicon	Tungsten
			Pailou, China	Araxá, Brazil	Chengde, China	Jiangsu, China	Nui Phao, Viet Nam
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	Brazil: medium natural accident hazard	China: high natural accident hazard	China: high natural accident hazard	Viet Nam: medium natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	Low water stress	Medium water stress	High water stress	Low water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium EPI	Brazil: medium EPI	China: medium EPI	China: medium EPI	Viet Nam: medium EPI
Value chain	Carbon footprint (kton CO_2 eq/application)		1.3E+05	9.6E+02	2.7E+03	1.5E+02	7.5E+02
	Cumulative Energy Demand (TJ/application)		4.4E+05	1.3E+04	4.2E+04	4.3E+03	7.9E+03
	Human toxicity, cancer and non-cancer (CTUh/application)		2.8E+04	4.9E+02	3.6E-01	2.2E+01	2.0E+03
	Terrestrial acidification (kton SO_2 eq/application)		5.3E+01	4.1E+00	1.1E+01	7.8E-01	1.7E+01
	Freshwater eutrophication (kton P eq/application)		4.4E+00	2.8E-01	3.5E-05	3.9E-02	5.5E-04

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([38]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([39]), AZE sites: 2018 - 2020 American Bird Conservancy ([40]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), magnesium: Peters et al., 2005; Ferro and Saccone, 2008, China Magnesium Corporation ([41]), niobium: Oliveira et al., 2001; Ferro and Saccone, 2008; El Hajj et al., 2019; Bonotto, 2020, U.S. Geological Survey ([42]), vanadium: Ferro and Saccone, 2008; Sun et al., 2009; Li et al., 2018, silicon: Ferro and Saccone, 2008; Boussaa et al., 2016, WorldAtlas ([43]), tungsten: Ferro and Saccone, 2008; Nguyen et al., 2020, Mining Global Magazine ([44])

[38] https://risk.preventionweb.net/
[39] https://www.protectedplanet.net/
[40] https://zeroextinction.org/site-identification/2018-global-aze-map/
[41] http://www.chinamagnesiumcorporation.com/our-business/magnesium-overview
[42] https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10254931
[43] https://www.worldatlas.com/articles/top-15-quartz-exporting-countries.html
[44] https://www.miningglobal.com/mining-sites/masan-resources-nui-phao-mine-worlds-largest-tungsten-mine

5.3.2 Impact of applications from a lifecycle perspective

The contribution of the critical raw materials to the environmental impact of an alloy depends on the type of alloy and the share of each critical raw material used. Few life cycle assessments specifically on alloys are available. Gómez et al. (2016) did a study on various aluminium casting alloys and found that silicon, together with copper and tin, are the alloying elements with the highest environmental impact. For silicon, this is due to the larger share of silicon, about 5–12 %, compared to, for example, the about 0.1-3 % share of copper. Magnesium was found to have a relatively high impact per kilogram, though a bit lower than copper, but due to its low content of around 0.1-0.6 %, it had an overall low contribution to the impact of the aluminium casting alloys studied. An example of the carbon footprint of an aluminium alloy with a high share of alloying critical raw materials (12 % silicon and 0.2 % magnesium) is shown in Figure 5-2. The contribution to the end application is not shown, as a large variety of applications are possible.

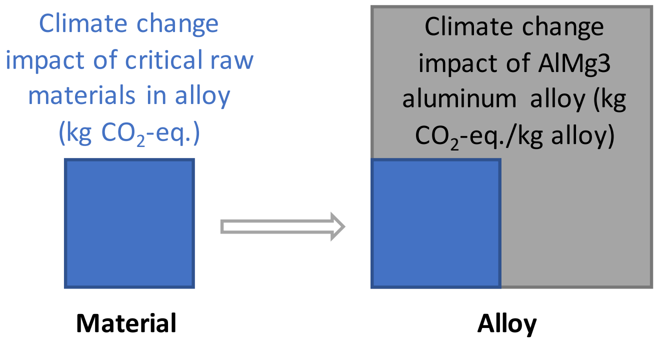

Figure 5-2. The contribution of critical raw materials to the impact on climate change of an application in an aluminium alloy ([45])

Source: based on Gómez et al. (2016) and Ecoinvent v3.6 (2019)

5.4 Substitution solutions

5.4.1 Element-to-element and material-to-material based substitution solutions

Substitution solutions exist for most critical raw materials used in alloys in the transport sector, although the substitution is often associated with a loss of quality. In addition, some of the potential substitution options are critical raw materials themselves. The potential element-to-element and material-to-material based substitution solutions for different alloys and the critical raw materials involved are described in the following paragraphs.

High-strength and stainless steels

Niobium in high-strength low alloy steel can be (partly) replaced with molybdenum, titanium, or vanadium (USGS, 2020; Tercero et al., 2015). Niobium, titanium and vanadium are microalloying elements in high-strength low alloy steel that affect ferrite strengthening by grain refinement, precipitation hardening and solid solution strengthening. Niobium is the element that most effectively

[45] The first block shows the greenhouse gases due to the production of the critical raw materials (silicon and magnesium) needed to produce a kilogram of a specific AlMg3 alloy. In the next lifecycle step stage of the life cycle, the greenhouse gases that are related to other materials, energy use, direct emissions and waste are added. Data are obtained from Gómez et al. (2016) and Ecoinvent v3.6 (2019). The share of the critical raw materials in the total climate change impact of this alloy is about 21 %.

increases the non-crystallisation temperature, and thus its substitution in high-strength low alloy steel may result in performance loss (Vervynckt et al., 2012).

Niobium in stainless steel can be substituted with tantalum, titanium or molybdenum as alloying element (USGS, 2020), although they may increase costs. In addition, high-nitrogen stainless steels can be substitutes for niobium-containing stainless steels in many applications due to their high strength and ductility, improved corrosion resistance and increased high temperature tensile strength (Tercero et al., 2015).

The use of vanadium as an alloying element in steels can be, to some extent, replaced by manganese, molybdenum, niobium, titanium and tungsten (USGS, 2020).

Aluminium alloys

Due to the unique properties of magnesium-containing aluminium alloys it is often difficult to substitute magnesium, especially in applications where longer lives and higher durability are required (Neelameggham and Brown, 2014). However, different strategies for substituting magnesium in aluminium alloys can be identified: using other allying elements in the same aluminium alloy series, using different aluminium alloy series, with reduced or no magnesium, or the using of entirely different materials (Tercero et al., 2015). In vehicles, reinforced plastics can provide similar performance to aluminium alloys containing magnesium but at higher cost. In addition, steel and titanium are possible substitutes for aluminium alloys containing magnesium (European Commission, 2017b).

Magnesium alloys

High price and poor corrosion resistance of magnesium alloys have hindered more widespread use in vehicle applications. Other high-strength, low weight alloys – high-strength low alloy and advanced high-strength steels, and aluminium alloys – can be used as substitutes for magnesium alloys (Karhu et al., 2019)

Cobalt alloys (stellites)

Possible material-to-material substitution solution for cobalt alloys include fibre-reinforced metal matrix composites (MMC), ceramic-ceramic and carbon-carbon composites, titanium aluminides, nickel-based single crystal alloys or iron-based super-alloys. The feasibility of substitution depends on the application, and reduced performance especially at high temperature can be expected. In addition, molybdenum is a potential substitute for tungsten in cobalt alloys (Tercero et al., 2015).

Copper beryllium alloys

Copper beryllium alloys may be substituted with copper alloys containing nickel and silicon, tin, titanium or other alloying elements, or phosphor bronze alloys (copper-tin-phosphorus) (USGS, 2020). These substitutions, however, usually result in reduced performance. As beryllium is a rather expensive metal, it is typically only used in applications where high reliability is required, and thus cannot be easily substituted due to reduced performance (Tercero et al., 2015).

The potential element-to-element and material-to-material based substitution solutions are summarised in Table 5.2.

Table 5.2. Substitution solutions for alloys used in transport sector.

Alloy type	Critical raw materials included	Potential element-to-element substitutes	Potential material-to-material substitutes
High-strength low alloy steel (HSLA) Advanced high-strength steel (AHSS)	Niobium	Partial substitution by titanium, vanadium, molybdenum	
	Vanadium	Manganese, molybdenum, nickel, titanium, tungsten	
Stainless steels	Niobium	Titanium, tantalum, molybdenum	high-nitrogen stainless steel
Aluminium alloys	Magnesium		Aluminium alloys (of same or different series), HSLA/AHSS, reinforced plastics
Magnesium alloys	Magnesium		Aluminium alloys, HSLA/AHSS
Copper alloys	Beryllium	Nickel, silicon, tin, titanium	
Cobalt alloys	Cobalt		Fibre-reinforced metal matrix composites, ceramic-ceramic and carbon-carbon composites, titanium aluminides, nickel-based single crystal alloys or iron-based super-alloys

Source: Grilli et al. (2017); Tercero et al. (2018); Karhu et al. (2019)

5.4.2 Secondary raw materials

In alloys, secondary raw materials provide a variable supply source depending on the critical raw materials. Since they often act as an alloying element providing special properties, their content is often low which makes them a challenging to recover from post-consumer scrap.

For magnesium, secondary magnesium is an important part of the global supply. In the EU, mostly new scrap from manufacturing is recycled. As there is often a relatively large proportion of magnesium in aluminium alloys, post-consumer magnesium scrap is recycled as a part of the aluminium value stream (European Commission, 2017b).

Niobium is used mainly in the form of ferroniobium by the steel industry. As the concentration of niobium in high-strength low alloy steel is very low and the recycling of steel is often optimised based on other aspects than maximum niobium recovery, it dilutes in the steel (Kurylak, 2016). As a result, functional recycling of niobium does not exist. However, niobium recycling from manufacturing scrap does occur (Kurylak et al., 2016).

As a significant share of vanadium is used in the same way as niobium in high-strength low alloy and advanced high-strength steels, its recycling from such post-consumer scrap as end-of-life vehicles is minimal (Petranikova et al., 2020). Vanadium recycling from manufacturing scrap does take place as concentrations are typically higher than in post-consumer scrap and the composition is known (Sundqvist Öqvist et al., 2018; European Commission, 2017b).

Beryllium is not currently recycled from post-consumer products as it is used in very low quantities and further dilutes in the treatment ending in the slag fraction. It can, however, be recovered from alloy production scrap as it is attractive from economic and energy points of view (BeST, 2016b).

5.4.3 Environmental impacts

Environmental impacts and risks do not seem to be drivers of critical raw material substitution in alloys. Substituting niobium in high-strength steels and stainless steels with molybdenum, tantalum, titanium or vanadium, neither significantly decreases the environmental risks, even if similar quantities are used nor affects the performance. Niobium has a high risk on three indicators, of which one is related to the mining operations (Table 5.3), while molybdenum, tantalum and titanium have a high risk on two related to the mining operations and vanadium on one (Table 5.1). When looking at the environmental impacts over the whole value chain, an impact reduction of human toxicity and freshwater eutrophication could be achieved by replacing niobium with vanadium. Nevertheless, the carbon footprint, cumulative energy demand and terrestrial acidification impacts would increase.

Although different strategies for substituting magnesium in aluminium alloys exist, these will probably not be beneficial for the environment as magnesium has a relatively low environmental risk and impact. It only has a high environmental impact on the value chain indicators due to the very large quantities that are used to produce alloys. As its impact per kilogram is relatively low, it will be difficult to find alternative materials with an even lower impact or that are needed in smaller quantities to serve the same function.

Table 5.3 Evaluation of the environmental hazard potential of critical raw material substitutes in alloys ([46])

	Goal	Indicator	Molybdenum	Titanium	Tantalum
			Luming, China	Hainan, China	Rubaya, DRC
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element, deposit contains some sulphur.	Lithophylic element	Lithophylic element
		Paragenesis with heavy metals	Deposit contains copper	Titanium may be associated with chromium	No indications that tantalum is associated with heavy metals.
		Paragenesis with radioactive components	No indications that molybdenum is associated with elevated levels of uranium and thorium	No indications that titanium is associated with elevated levels of uranium and thorium	High concentrations of radioactive elements are measured in columbite-tantalite in North Kivu
Technology	Limiting direct impacts on ecosystems	Mining method	Open pit	Unconsolidated sediment mining	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Widely used depressants include sodium sulfide, sodium	Mainly gravity, magnetic and electrostatic separation	Generally extracted by gravimetric methods, also use

[46] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

	Goal	Indicator	Molybdenum	Titanium	Tantalum
			Luming, China	Hainan, China	Rubaya, DRC
			hydrosulfide, cyanide and Nokes reagents		of flotation and magnetic separation
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	China: high natural accident hazard	DRC: low natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	Low water stress	Low water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	Very close to AZE Lake Kivu, Rwenzori Mountains and Virunga National Park sites
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium EPI	China: medium EPI	DRC: low EPI

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([47]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([48]), AZE sites: 2018 - 2020 American Bird Conservancy ([49]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), molybdenum: Wang et al., 2015; Zhigang et al., 2017, China Railway Group Limited ([50]), titanium: Ferro and Saccone, 2008; Dehoust et al., 2017, U.S. Geological Survey ([51]), KYOCERA SGS Precision Tools Europe ([52]), tantalum: (Černý and Ercit, 1989; Mustapha, Mbuzukongira and Mangala, 2007; Ferro and Saccone, 2008; Dehoust *et al.*, 2017), PROMETIA ([53])

Secondary raw materials

As for all applications, using secondary critical raw materials to produce alloys can result in large environmental savings as with recycled material inputs, the risks related to mining are eliminated. Furthermore, the energy needed to produce recycled metals is generally much lower, typically by 60–95 %, than the amount needed to produce primary metals, resulting in lower environmental impacts (Norgate, 2013).

[47] https://risk.preventionweb.net/
[48] https://www.protectedplanet.net/
[49] https://zeroextinction.org/site-identification/2018-global-aze-map/
[50] http://www.crecg.com/english/2745/2804/41514/index.html
[51] https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10231339
[52] https://kyocera-sgstool.co.uk/titanium-resources/titanium-information-everything-you-need-to-know/titanium-ores/
[53] http://prometia.eu/wp-content/uploads/2017/03/9_MSP-REFRAM-Tantalum-Niobium-production-SotA_F.-Bourgeois.pdf

6 Mineral fertilisers

Efficient agriculture and high crop yields are needed to secure the food supply for world's growing population. At the same time, dietary habits are changing, and meat and dairy consumption is rising, thus fertiliser consumption is expected to increase in the future. Nitrogen based fertilisers are the largest group used in Europe, 67 % by weight in 2018, followed by phosphate (P_2O_5), 16 % by weight, and potash (K_2O), 17 % by weight, based fertilisers (Fertilizers Europe, 2019). In the EU, 1.3 million tonnes of phosphorus fertiliser were used in agriculture in 2017, however, its consumption has fallen by 9 % since 2007, whereas the consumption of nitrogen fertilisers has increased by 8 % (Eurostat, 2017). On global level, the use of phosphorus and potassium based fertilisers is increasing by 2 % a year and more for nitrogen based fertilisers (European Commission, 2019).

6.1 Critical raw materials in applications

Macronutrients are essential elements for normal plant growth and are required in large amounts, whereas micronutrients are required in relatively small amounts. Mineral fertilisers are based on one or more macronutrients – nitrogen, potassium and phosphorus. In addition, several micronutrients can be included such as iron, zinc, boron and copper (Hossner, 2008). Phosphorus is produced from phosphate rock and boron from borate minerals, both of which are listed as critical raw materials (European Commission, 2017b).

Phosphorus is a vital element for all life, including plant growth, animals and humans. Phosphate fertilisers are needed to ensure high crop yields, and different types of fertiliser are available with varying properties such as composition, release rate, etc. The main phosphate fertilisers used in agriculture include diammonium phosphate (DAP), monoammonium phosphate (MAP), single superphosphate (SSP) and triple superphosphate (TSP). In the production of superphosphate fertilizers, phosphate rock is reacted with strong acids such as sulphuric acid for single superphosphate or phosphoric acid for triple superphosphate, whereas ammonium phosphates are produced by reacting ammonia with phosphoric acid (de Boer et al., 2019).

Eighty-six per cent of phosphate rock production is used for fertilisers (European Commission, 2017b) and it is considered to have a high supply risk as its production is concentrated in three countries, China, Morocco and the United States, that account for 70 % of global production. In addition, production is concentrated among a small number of producer companies with large market shares (Tercero, 2019; European Commission, 2017b). The global distribution of phosphorus reserves is uneven as 73 % are located in Morocco and the Western Sahara (European Commission, 2017b).

Boron is an essential micronutrient for plant growth, crop yield and seed development (European Commission, 2017b) and fertilisers containing it are needed in boron-deficient soils (Tercero et al., 2018). Using the 2010–2014 average, 13 % by weight of the end-use of borates in the EU is for fertilisers (European Commission, 2017b).

6.2 Economic importance and future aspects

6.2.1 Economic importance

In the report, economic importance reflects how critical raw materials used in the application generate economic importance to the European economy, based on the European Commission's 2017 assessment of critical raw materials. The distribution of economic importance of those used in mineral fertilisers is shown in Figure 6-1. It describes the share of the application in the economic importance of these particular materials.

Figure 6-1. The contribution of mineral fertilisers to the economic importance of critical raw materials, per cent

Source: ETC/WMGE based on European Commission (2017b)

Mineral fertilisers account for a major share of around 85 % in the economic importance of phosphate rock whereas for borate fertiliser's share is around 24 %. The distribution for phosphate rock is unsurprising given its heavy use in agriculture while borates are used more widely and therefore the importance of fertilisers is lower.

6.2.2 Future aspects

The global food demand, mainly driven by population growth even though that is showing some indications of slowing down, is predicted to grow more slowly in the coming decade than in the previous one. Food consumption per person is expected to increase more slowly as it approaches saturation levels in some places (OECD/FAO, 2019).

The International Fertilizer Association (IFA) has projected that global phosphate rock supply will grow from 235 million tonnes in 2018 to 254 million tonnes in 2023, an increase of 8 %, with Africa accounting for 75 % of the net increase. The global supply of phosphoric acid is expected to grow 1.5 % per year between 2018 and 2023, while demand will grow 1.4 % per year (IFA, 2019).

The Food and Agriculture Organization of the United Nations (FAO) has estimated the compound annual growth rates for phosphorous and phosphoric acid in Europe as 2.1 % and 2.0 % respectively between 2018 and 2022 (FAO, 2019).

It has been predicted that the global demand for boron for agricultural purposes will reach 326,860 tonnes by 2023 – a compound annual growth rate of 1.4 % between 2015 and 2023, indicating a modest increase (Statista, 2015).

6.3 Environmental aspects

6.3.1 Risks and impacts of critical raw materials in applications

The critical raw material used to produce fertilisers are phosphate rock to obtain phosphorus and borate minerals to obtain boron. The environmental hazard potential of these is shown in Table 6.1. Both have medium and high environmental hazard potentials for at least 11 indicators. They present high pollution risks at mining sites, for phosphate there is a high natural accident risk and for boron there is a high risk that mining could cause water stress. These materials have a high impact on the value chain indicators, such as the carbon footprint, as they are used in large quantities to produce fertilisers. Both phosphate and boron are generally produced in countries with medium Environmental Performance Index ratings, increasing the likelihood that all necessary measures to protect the environment are not taken.

Table 6.1. Evaluation of the environmental hazard potential of critical raw materials in fertilisers ([54])

	Goal	Indicator	Phosphate Kaiyang, China	Boron Bigadiç, Turkey
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element, association can contain sulfides, not clear if this is the case for this deposit	Lithophylic element in colemanite, tincal and ulexite
		Paragenesis with heavy metals	Arsenic, cadmium, chromium, lead, mercury and nickel are frequently associated with phosphate rock	Groundwater in the mining area has been found to be contaminated with arsenic
		Paragenesis with radioactive components	High radioactivity has been found in a sample of Kaiyang	No indication that boron is associated with elevated levels of uranium and thorium
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Processing with acid	Extraction generally involves acid
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	Turkey: medium natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	High water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites

[54] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium EPI	Turkey: medium EPI
Value chain	Carbon footprint (kton CO_2 eq/application)		1.6E+04	4.9E+02
	Cumulative Energy Demand (TJ/application)		2.9E+05	8.8E+03
	Human toxicity, cancer and non-cancer (CTUh/application)		3.1E+03	9.1E+01
	Terrestrial acidification (kton SO_2 eq/application)		6.7E+01	2.1E+00
	Freshwater eutrophication (kton P eq/application)		8.8E+00	1.7E-01

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([55]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([56]), AZE sites: 2018 - 2020 American Bird Conservancy ([57]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), phosphate: Ferro and Saccone, 2008; International Atomic Energy Agency, 2015; Reta et al., 2018, U.S. Geological Survey ([58]), boron: Kar, Şen and Demirbaş, 2006; Gemici et al., 2008; Kuskay and Bulutcu, 2011

The mining of phosphate rock has several negative effects on the environment (Reta et al., 2018). As with most surface mining operations, phosphate rock mining has impacts on the landscape and on ecosystems close to the mines (Schroder et al., 2010). Even though countries generally require mining companies to restore the land after the mines are exhausted, this is not always done in practice (Diemer et al., 2018). For example, many closed phosphate mines in Morocco have no post-closure management plan, meaning that mining waste is still on site and no restoration activities have taken place (Diemer et al., 2018). Another example is the Republic of Nauru, a small island in the southwestern Pacific Ocean, where the environment was critically damaged by mining for phosphate rock. Biodiversity-rich habitats were destroyed, and no post-mining restoration strategies are in place (Diemer et al., 2018). The water use of the phosphate mining industry may disturb the local hydrology (Reta et al., 2018). This is especially relevant in regions were water is scarce, which is the case in Jordan and the Western Sahara, regions with some of the largest phosphate reserves (Schroder et al., 2010). Additionally, mining of phosphate rock generates large amounts of waste containing toxic metals and radioactive elements (Reta et al., 2018). Furthermore, phosphogypsum, a hazardous by-product of the production of fertiliser from phosphate rock, is dumped in stockpiles that can lead to serious pollution of groundwater due to leakages (Diemer et al., 2018; Schroder et al., 2010). Lastly, dust, fluoride and radon gas emission result in air quality problems (Reta et al., 2018).

6.3.2 Impact of applications from a lifecycle perspective

The environmental impacts of phosphorus fertilisers over their lifecycles are mainly due to the release of carbon dioxide from the reaction of phosphorites with sulfuric acid, and the use of fossil fuels for the production and transport of raw materials and products (Skowronska and Filipek, 2014). Eutrophication is caused by the dispersion of phosphates during fertiliser production, the release of phosphates from applied fertiliser into surface water and from phosphogypsum stockpiles

[55] https://risk.preventionweb.net/
[56] https://www.protectedplanet.net/
[57] https://zeroextinction.org/site-identification/2018-global-aze-map/
[58] https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10239757

(Skowronska and Filipek, 2014). Phosphate fertilisers may also contain heavy metals, mainly cadmium, which enter agroecosystems as a result of fertilizer application (Skowronska and Filipek, 2014).

The contribution of the mining of phosphorus and borates to the environmental impact of the fertilisers throughout their lifecycles appear to be relatively small. A calculation of the impact of the production of a single superphosphate fertiliser in the Ecoinvent v3.6 database shows that the production of beneficiated phosphate rock contributes about 10 % to the impact in most categories (ReCiPe 2016 method) (Figure 6-2).

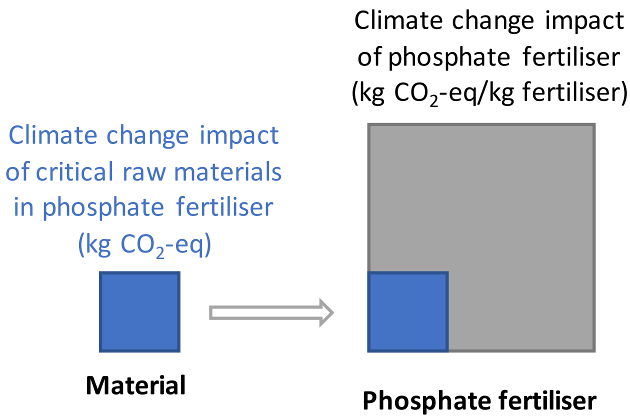

Figure 6-2 The contribution of the critical raw materials to the impact on climate change of the application in fertiliser ([59])

Source: based on Ecoinvent v3.6 (2019)

6.4 Substitution solutions

Both phosphorus and boron are essential nutrients for plants. Phosphorus has an irreplaceable role in a plant's metabolism, structure, and reproduction, whereas boron is indispensable in promoting optimum growth, development, yield, and quality (Brown et al., 2002; Day and Ludeke, 1993). Thus, the elemental substitution of phosphorus or boron in crop cultivation is not possible (Cordell and White, 2013). There are, however, ways of reducing the phosphorus consumption (Sections 6.4.1-6.4.3)

6.4.1 Increasing the efficiency of the food chain

The fertiliser consumption on a global level can be reduced by improving the efficiency of food production and reducing food loss and food waste along the food chain. According to the FAO, food loss refers to the decrease in the quantity or quality of food resulting from actions at the beginning of food chain – during farming, and pre- and post-processing of food, while food waste describes the decrease in the quantity or quality of food caused by actions at the end of food chain – by retailers, food service providers and consumers (FAO, 2020).

[59] The first block shows the greenhouse gases generated in the production of the critical raw material, phosphate rock, needed to produce a kilogram of single superphosphate fertiliser. In the next stage of the lifecycle, the greenhouse gases that are related to other materials, energy use, direct emissions and waste are added. Data are obtained from Ecoinvent v3.6 (2019). The share of the critical raw materials in the total climate change impact of this fertiliser is about 12 %.

It has been estimated that one-third of all food produced globally is lost or wasted and only one-fifth of the phosphorus extracted for food production ends up in the food consumed by people each year (FAO, 2020; Cordell and White, 2013). Phosphorus is lost at all stages of the food chain and some of these losses are unavoidable, such as inedible crop fractions – peels, husks, etc. Many of the losses, however, could be avoided as they result from inefficient practices, such as fertilizer spillages or food spoilage (Cordell and White, 2013).

Phosphorus mining

The estimates of the average losses during phosphorus mining vary between 15 % and 50 %. Phosphorus losses in the mining stage mainly arise from the beneficiation process in which contaminants are removed and from spillages during storage and transport. It is, however, unclear how many of these losses could be avoided, for instance, by improved mining methods and equipment, and developments in beneficiation methods (Steiner et al., 2015; Cordell and White, 2013).

Fertiliser production

The largest share of phosphorus loss during fertiliser production is associated with the generation of phosphogypsum, a by-product in which radioactive isotopes are concentrated. Some authorities consider the radioactivity levels in phosphogypsum too high for reuse as gypsum, thus the by-product is stockpiled as a dry or wet stack (Cordell and White, 2013). According to Fuleihan (2012), countries such as Mexico, Morocco, South Africa and Tunisia discharge the phosphogypsum into the sea. More than 200 million tonnes of phosphogypsum are produced in the world each year, translating to an annual increase of approximately 700,000 tonnes of stockpiled elemental phosphorus (Cordell and White, 2013; Fuleihan, 2012). It is, however, unclear how much the amount of generated by-product and its phosphorus content could be reduced by process improvements (Cordell and White, 2013).

Figure 6-3 Phosphogypsum pile in Florida, United States.

Credit: Harvey Henkelmann

Agriculture

The optimisation of phosphorus use in agricultural soil is challenging for many reasons, such as the complexity of phosphorus soil chemistry, varying characteristics of soil, and different practices in land use and management. Normally, only 15–30 % of the phosphorus applied as a fertiliser reaches the crop, highlighting the potential for increasing the efficiency of its use, and substantially reducing overall demand. Moreover, increasing the efficiency of phosphorus use is likely associated with benefits such as increased agricultural productivity, reduced freshwater eutrophication and improved economics of farming (Cordell and White, 2013).

The means for reducing losses or demand for phosphorus fertilisers in agriculture include (Cordell and White, 2013):

- correct placement of fertiliser to maximise the accessibility of plant roots to the phosphorus;
- correct application time of fertiliser in respect of the growing season and stage of plant growth;
- correct application rate of fertiliser in respect of the soil and plant needs;
- testing of soil to determine the fertiliser needs;
- applying microbes and enzymes that increase phosphorus uptake by roots;
- optimising soil characteristics, such as pH, moisture and aeration, to maximise the amount of dissolved phosphorus – the form available to plants;
- reduction of erosion by, for instance, buffer strips (adjacent areas of land with permanent vegetation that slow run-offs, cover crops), minimising tillage, maintaining root-soil structure and mulching; and
- breeding and selecting plants that have better ability to access phosphorus or produce more with the same amount of phosphorus accessed.

New ways of farming, such as using hydroponics, can potentially also help reduce the fertiliser demand. Hydroponics is a technique in which plants are grown in circulated, nutrient-containing water instead of soil (dos Santos et al., 2013) (Figure 6-4). It is claimed to offer numerous advantages, such as fast growth, high productivity, easy management and more efficient fertiliser use (dos Santos et al., 2013; Asao, 2012).

Figure 6-4 Lettuce grown in hydroponics system

Credit: marsraw (pixabay.com)

6.4.2 Changing diets

Diets based on meat and dairy, which are phosphorus intensive, can have a large impact on the phosphorus demand. The conversion of crop to meat protein is inefficient in terms of phosphorus utilisation as only a minor part of the phosphorus ends up in edible components rather than manure, bones and blood (Cordell and White, 2013). As a result, diets based on meat and dairy require up to three times more phosphorus than vegetarian diets. An Australian case study, for example, estimated a reduction of over 70 % in the phosphorus footprint by changing from a meat and dairy-based diet to a vegetarian one (Metson et al., 2016). Meat consumption, however, is predicted to grow, especially in developing countries with large middle classes in Asia, Latin America, and the Middle East due to income and population growth (OECD/FAO, 2016).

In some cases, the phosphorus consumption related to the production of pork and poultry can be reduced by adjusting livestock diets (Tirado and Allsopp, 2012). Typically, higher amounts of phosphorus are contained in the diet of animals than can be effectively utilised, resulting in a high amount of phosphate ending up in manure.

6.4.3 Secondary raw materials

The recycling rates of phosphorus to replace phosphate rock are generally low. The exception is manure in animal production which is almost entirely recycled in Europe (Dijk et al., 2016). The following paragraphs describe the potential secondary sources for phosphorus.

Phosphorus recovery from tailings and phosphogypsum

Phosphorus can potentially be recovered from various wastes originating from phosphate rock mining, as well as from phosphogypsum, the by-product of fertiliser production (Cordell and White, 2013). According to Cordell and White (2013), the feasibility of extracting the phosphorus from piled phosphogypsum safely is "unclear and under investigation" and to date, such commercial processes are not cited in the literature. There is, however, a patent describing a method based on bioleaching that claims to be able to leach phosphorus and rare-earth elements very efficiently from phosphogypsum (Viktorovna et al., 2012).

Phosphorus recovery from biowaste – crop and food waste

Annually around 88 million tonnes of food waste are generated in Europe, of which 53 % originates from households (Stenmarck et al., 2016). Food waste in municipal solid waste is a major source of phosphorus containing approximately 4 grams of phosphorus per kilogram in total solids (Kalmykova and Karlfeldt Fedje, 2013). However, to date there seem to be few commercial examples of the recovery of phosphorus from food waste, municipal solid waste or its ashes (Yli-Rantala, 2018).

Phosphorus recovery from manure

Animal manure, as well as other parts of animals such as blood and bones, are widely used as a source of phosphorus fertiliser in agriculture (Tirado and Allsopp, 2012). Animal manure is applied either directly to land or as fertiliser derived from it. However, there are several disadvantages in directly substituting inorganic fertilisers with manure such as higher transportation costs, difficulty in defining the appropriate manure application rate, the risk of transmitting pathogens and the effects of undesirable odour (Scholz et al., 2014).

Phosphorus recovery from municipal wastewater

It has been estimated that the human population produces approximately 1–1.5 grams of phosphorus per person per day human excreta (Cordell and White, 2013). The removal of phosphorus from municipal wastewater is well established and widely applied. Typically, 80–90 % of influent phosphorus in wastewater is transferred to sludge solids, however the destination of the sewage sludge varies (Dijk, Peter and Oenema, 2016; Scholz et al., 2014). There are a number of commercial processes in use that recover phosphorus from wastewater (Yli-Rantala, 2018).

Phosphorus recovery from industrial waste

Phosphorus is used for various applications in the chemical industry, although the share is minor compared to its use in agriculture (European Commission, 2017b). Industrial waste and wastewater offer some opportunities for phosphorus recovery; nonetheless very little phosphorus is recovered from non-food related production (Dijk, Peter and Oenema, 2016).

6.4.4 Environmental impacts

Although the elements in fertilisers are not substitutable with others, it is possible to recover phosphorus from waste streams. The driver of this seems mainly to be concerns about depletion rates of phosphate rock in current mining zones in North Africa, the Middle East, the United States of America and China, rather than being environmentally motivated. Recent studies have found that large differences exist between technologies for the recovery of phosphate from wastewater. There appear to be some trade-offs – recovery from liquid digester supernatant/dissolved phosphorus in anaerobic effluent results in few greenhouse gas emissions and little demand for energy but the recovery potential is low; conversely, recovery from sewage sludge results in high greenhouse gas emissions and demand for energy but recovery rates are higher (Amann et al., 2018). Overall, however, sludge-based fertiliser currently has higher environmental impacts than mineral phosphorus fertiliser (Pradel and Aissani, 2019). Recovery from sewage sludge ash appears to have the greatest potential for efficient phosphorus recycling, with various technologies having lower environmental impacts than the extraction of primary phosphorus (Amann et al., 2018).

7 Electronic components (printed circuit assembly)

Various critical raw materials are used in electronic components such as integrated circuits, semiconductors, light-emitting diodes, alloying electronics, solders, ceramic capacitors, electric components, etc. Due to the diversity of electronic components, the focus in this report is limited to printed circuit boards (PCBs) due to their relevance in electronics and because they comprise several components which incorporate critical raw materials.

Printed circuit boards, also called printed wiring boards or printed circuit assemblies, are key components in nearly all electrical and electronic equipment. They consist of:
1) a non-conducting substrate/laminate which is typically made of glass-fibre reinforced epoxy resins;
2) a conducting layer typically composed of copper; and
3) components attached to the substrate (Ghosh et al., 2015).

Components include light emitting diodes, transistors, capacitors, diodes, integrated circuits, connections, and other units (Karhu et al., 2019).

Printed circuit boards can be classified as single-sided, double-sided or multi-layered, depending on the structure and alignment. Their chemical composition varies according to the type and the components involved, but in general they are mainly made of metals, copper, iron and aluminium, plastics, ceramics and glass. In addition, several precious metals and critical raw materials are included in small amounts (Ghosh et al., 2015).

Printed circuit boards accounted for 5 % of the total mass of waste electrical and electronic equipment generated in Europe in 2015 (Korf et al., 2019). Due to rapid miniaturisation of components in electrical and electronic equipment, the average weight of printed circuit boards is decreasing (Huisman et al., 2017).

7.1 Critical raw materials in applications

Various critical raw materials are found in printed circuit boards, some of the most important ones being palladium, gallium, tantalum and beryllium (Karhu et al., 2019). In addition, antimony, barium, gallium, indium, iridium, niobium, platinum, ruthenium, silicon and yttrium may also be present in varying amounts (Karhu et al., 2019; Tercero et al., 2018; 2015). It should be noted that the application/devices in which the printed circuit board is mounted will significantly affect the critical raw material content. The printed circuit board of a coffee maker, for example, is simple and may not require components containing critical raw materials whereas the printed circuit board of a high-tech device such as a mobile phone or a laptop requires several components such as microchips which utilize critical raw materials. In addition, critical raw materials are often used in low quantities in printed circuit boards but nonetheless often provide essential functions enabling, for example, the miniaturisation of components. The use of some essential critical raw materials in printed circuit boards is described in the following paragraphs.

Palladium (Pd) is used in electronics, especially in multilayer ceramic capacitors (MLCC), the most common design of ceramic capacitors, which have been one of key technologies in enabling the miniaturisation of electronics (EPCI European Passive Components Institute, 2020). Internal electrodes in multilayer ceramic capacitors are based on either precious metals, palladium, or palladium-silver, or base metals such as nickel (Pan and Randall, 2010). The size reduction of multilayer ceramic capacitors and thinner layers of palladium have led to a decrease in the amount of palladium in printed circuit boards over the years. In case of random access modules (RAM), for example, an 80 % reduction in palladium content was observed during 1991–2008 (Charles et al., 2017). In addition to capacitors, palladium is used in microprocessors, for electronic contacts on the surfaces of printed circuit boards and on the copper wires used for bonding electrical components to the boards due to its high chemical stability and good conducting properties (Işıldar et al., 2018; Tercero et al., 2018).

Several gallium (Ga) based compounds are used for type III-V semiconductors. These include gallium arsenide, gallium phosphide, gallium nitride and gallium antimonide materials, of which gallium arsenide and gallium nitride are most employed using almost 99 % of all gallium produced. Electrical and electronics equipment is the most important end use for gallium accounting for approximately 90 % of total production. In the sector, almost 68 % of the applied gallium is used for integrated circuits (Ueberschaar, Otto and Rotter, 2017). This type of semiconductor material is used in miniaturised integrated circuits for high-frequency power amplifiers for wireless communication, such as mobile phones or wireless local area networks (WLAN) hardware (Chancerel et al., 2015). In addition, opto-electronic components such as light emitting diodes or laser diodes are important end use application for gallium (Ueberschaar et al., 2017).

Tantalum (Ta) capacitors are another widely employed capacitor type for electronic applications. Ta is used for tantalum capacitor anodes which consist of sintered tantalum with a thin layer of tantalum pentoxide (Ta_2O_5) on the surface (Ueberschaar et al., 2017). The high relative permittivity of tantalum pentoxide enables the capacitors' high capacity (Chancerel et al., 2015). As a result, smaller capacitors can be manufactured for miniaturised and portable electronics, which are also robust, temperature tolerant and associated with low failure rates (Tercero et al., 2018). According to Chancerel et al. (2015), the mass fraction of tantalum in printed circuit boards has been reduced significantly in recent years due to component miniaturisation and other technological innovation. Laptop computers, desktop personal computers and smartphones are the most common electronic devices using Ta.

Beryllium is used, particularly in alloys with copper, to improve mechanical properties without weakening electrical or thermal conductivity (Karhu et al., 2019; European Commission, 2017b). Copper-beryllium alloys are used in electronic and electrical connectors in a wide range or sectors including consumer electronics, telecommunication and transportation (Karhu et al., 2019).

7.2 Economic importance and future aspects

7.2.1 Economic importance

In the report, economic importance reflects how critical raw materials used in the application generate economic importance to the European economy based on the EC's 2017 assessment on critical raw materials. The distribution of economic importance of these materials used in electronic components is presented in Figure 7-1, which describes the share of the application in the economic importance of these particular critical raw materials.

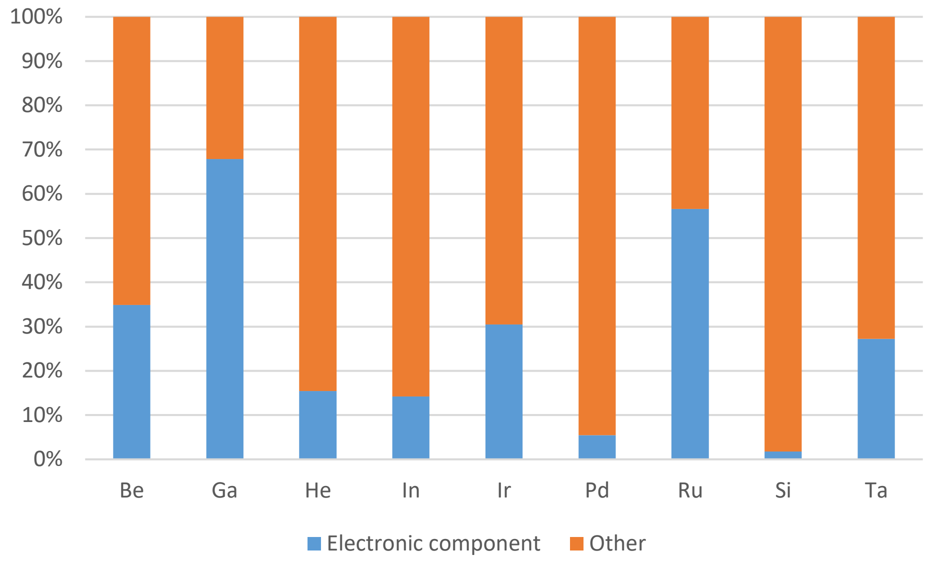

Figure 7-1 The contribution of electronic components to the economic importance of critical raw materials, per cent

Source: ETC/WMGE based on European Commission (2017b)

Electronic components utilise many different critical raw materials that generate varying economic importance to them. Gallium is the most important at slightly less than 70 % originating from electronic components. For ruthenium, electronic components generate around 57 % of its economic importance. When only taking electronic and telecommunication equipment into account, beryllium has a share of 35 %, but electronic components in other applications increase the reliance of the electronics sector on beryllium. Iridium and tantalum have shares of 31 % and 27 %, respectively. The rest of the elements have lower shares.

7.2.2 Future aspects

Europe is the third largest market for electronics and media in the world with revenues of EUR 72 billion in 2019. The average annual growth rate up to 2024 is estimated at 7.3 %, mainly driven by consumer electronics sales (Statista, 2020c).

On the other hand, as the demand of semiconductors for consumer electronics is saturating, other sectors, including the automotive sector and artificial intelligence, are providing semiconductor companies growth opportunities (Deloitte, 2019). In the automotive sector, the demand for safety-related electronics systems has grown explosively – semiconductor components required in these systems will cost USD 600 per car by 2022 (Deloitte, 2019).

7.3 Environmental aspects

7.3.1 Risks and impacts critical raw materials in applications

The most important critical raw materials used in electronic components are beryllium, gallium, palladium and tantalum. The environmental hazard potential of these is shown in

Table 7.1. All four have a high pollution risk at the mining site. Palladium extraction has a high or medium risk on all indicators related to pollution – acid drainage, pollution with heavy metals, radioactive elements and chemicals used for extraction. Nevertheless, it is mined underground, which causes less direct destruction of ecosystems as an open pit mining, which is the case for the three other materials. A high natural accident hazard exists in the main producing countries of gallium (China), and beryllium (United States of America). The largest beryllium mine in the world at Spor Mountain mine in Utah is in an area of high water stress. Most tantalum is mined in the Democratic Republic of the Congo and Rwanda, countries with a low score on the Environmental Performance Index. Palladium, tantalum and beryllium have a medium impact on most value chain indicators, such as the carbon footprint. The per kilogram footprint of these critical raw materials is also high, especially for palladium, for which the high impact is due to high power consumption during mining and ore beneficiation (IPA, 2013).

Table 7.1 Evaluation of the environmental hazard potential of the main critical raw materials in printed circuit boards ([60])

	Goal	Indicator	Palladium	Gallium	Tantalum	Beryllium
			Norilsk, Russia	Shanxi, China	Rubaya, DRC	Spor Mountain, USA
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element in sulphidic deposit	Chalcophilic element, however, in this case it is a by-product from bauxite	Lithophylic element	Lithophylic element
		Paragenesis with heavy metals	Palladium is associated with copper, nickel and heavy metals	Bauxite contains heavy metals such as chromium, niobium, lead, arsenics and Cd, soil in the mining area has been found to be contaminated with Cd	No indications that tantalum is associated with heavy metals	Mineralisation contains copper, lead and zinc
		Paragenesis with radioactive components	Thorium and uranium present in the Anabar shield, in relatively low concentrations	Average data on Chinese bauxite deposits suggest that they are often associated with slightly increased concentrations of uranium and/or thorium	High concentrations of radioactive elements are measured in columbite-tantalite in North Kivu	Mineralisation was also mined for uranium
Technology	Limiting the direct impacts on ecosystems	Mining method	Underground mining	Open pit	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Froth flotation using various chemicals	Digestion using sodium hydroxide solution in the Bayer process	Generally extracted by gravimetric methods, also use of flotation and magnetic separation	Sulfuric acid and thickeners are added to separate the beryllium, then solvent extraction is used
Natural	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes,	Russia: medium natural accident hazard	China: high natural accident hazard	DRC: low natural accident hazard	USA: high natural accident hazard

[60] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

	Goal	Indicator	Palladium	Gallium	Tantalum	Beryllium
			Norilsk, Russia	Shanxi, China	Rubaya, DRC	Spor Mountain, USA
		storms, landslides				
	Avoiding competition in water usage	Water Stress Index	Low water stress	Low water stress	Low water stress	High water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	Very close to Lake Kivu, Rwenzori Mountains and Virunga National Park AZE sites	Very close to Fish Springs National Wildlife Refuge
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	Russia: medium EPI	China: medium EPI	DRC: low EPI	USA: high EPI
Value chain	Carbon footprint (kton CO_2 eq/application)		1.0E+02	6.0E+01	1.1E+02	3.6E+02
	Cumulative Energy Demand (TJ/application)		1.9E+03	8.9E+02	1.9E+03	5.1E+03
	Human toxicity, cancer and non-cancer (CTUh/application)		3.7E+02	1.5E+01	5.1E+01	6.2E+01
	Terrestrial acidification (kton SO_2 eq/application)		3.5E+01	1.3E-01	7.3E-01	1.5E+00
	Freshwater eutrophication (kton P eq/application)		2.1E-01	1.8E-02	6.4E-02	9.1E-02

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([61]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([62]), AZE sites: 2018 - 2020 American Bird Conservancy ([63]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), palladium: Ferro and Saccone, 2008; Starostin and Sorokhtin, 2011, PorterGeo Database ([64]), MiningTechnology ([65]), DANAFLOAT ([66]), gallium: Ferro and Saccone, 2008; Dehoust et al., 2017; Xingshan, 2018, The Diggings ([67]), tantalum: (Černý and Ercit, 1989; Mustapha, Mbuzukongira and Mangala, 2007; Ferro and Saccone, 2008; Dehoust *et al.*, 2017), PROMETIA ([68]), beryllium: Ferro and Saccone, 2008; McLemore, 2010, U.S. Geological Survey ([69]), Mindat.org ([70])

[61] https://risk.preventionweb.net/
[62] https://www.protectedplanet.net/
[63] https://zeroextinction.org/site-identification/2018-global-aze-map/
[64] http://www.portergeo.com.au/database/mineinfo.asp?mineid=mn174
[65] https://www.mining-technology.com/projects/norilsk/
[66] http://www.danafloat.com/uk/mining_ores/platinum_palladium
[67] https://thediggings.com/mines/usgs10230813
[68] http://prometia.eu/wp-content/uploads/2017/03/9_MSP-REFRAM-Tantalum-Niobium-production-SotA_F.-Bourgeois.pdf
[69] https://pubs.usgs.gov/of/1998/ofr-98-0524/SPORMTN.HTM
[70] https://www.mindat.org/loc-37506.html

7.3.2 Impact of applications from a lifecycle perspective

The few life cycle assessments on printed circuit boards found do not include critical raw materials. In the Ecoinvent database, palladium is included in the production of printed circuit boards. For 1 kilogram of printed circuit board, 84 milligrams of palladium is needed. As this is a very small amount, the contribution to the total impact of printed circuit boards is negligible for all categories except terrestrial acidification for which critical raw materials contribute 4 % of the total impact of the printed circuit boards and particulate matter formation for which they contribute 7 % (Figure 7-2). Terrestrial acidification is caused by sulphur dioxide emissions to air during extraction and refining.

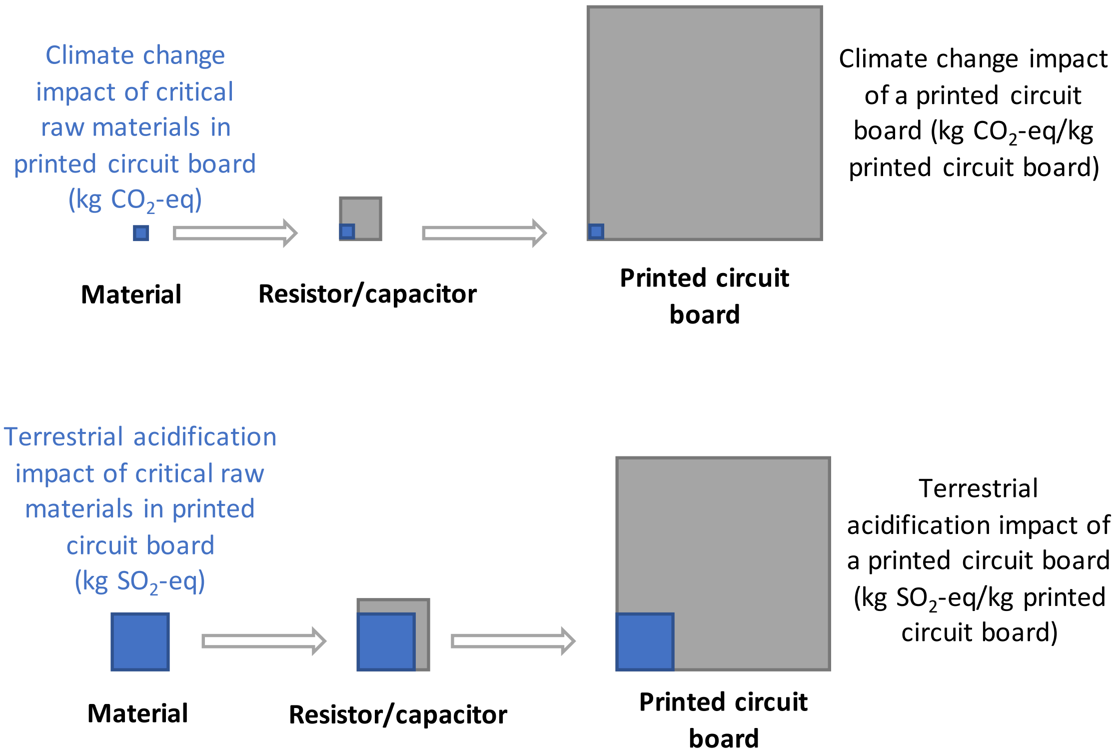

Figure 7-2 The contribution of critical raw materials to the impact on climate change (top) and terrestrial acidification (lower) in a printed circuit board ([71])

Source: based on Ecoinvent v3.6 (2019)

7.4 Substitution solutions

7.4.1 Element to element

Substituting critical raw materials in electronic components is difficult without losing performance properties. Among the four relevant materials, beryllium, gallium, palladium and tantalum, either performance losses or higher prices are expected when substitution is considered (Karhu et al., 2019).

[71] The first block shows the greenhouse gases/acidifying emissions due to the production of the critical raw materials needed to produce a kilogram of surface mounted, lead-free, printed circuit board. In the next stages of the life cycle, the greenhouse gases/acidifying emissions that are related to other materials, energy use, direct emissions and waste are added. Data are obtained from Ecoinvent v3.6 (2019). The share of the critical raw materials in the total climate change impact of a printed circuit board is about 0.3 %. For terrestrial acidification, this share is 7 %.

In the case of palladium, other platinum-group metals, gold or base metals such as nickel and copper are potential substitutes. However, an increase in price or trade-off in performance may need to be taken into account. Copper and nickel have been substituted for palladium in multilayer ceramic capacitors since the mid-1990s in some electronic devices, although with some reduction in performance. Because of this, applications that require high performance, such as military, medical and aerospace ones, still rely on palladium in multilayer ceramic capacitors (Nassar, 2015).

It is often suggested that gallium, as gallium arsenide or gallium nitride substrates in semiconductors, could be substituted with silicon or silicon base substrates such as silicon germanium. However, significant performance and efficiency losses are expected since silicon presents lower electron mobility (Pavel et al., 2016). In light-emitting diode applications, organic light-emitting diodes (OLED) could be a substitute for solid state light-emitting diodes (European Commission, 2017b). However, organic light-emitting diode technology is not expected to broadly penetrate the lighting market before 2025, as competitiveness in efficiency, price compared to light-emitting diode technology and lifetime considerations remain barriers (Pavel et al., 2016).

For tantalum, substituting it in capacitors usually means a change in capacitor technology. Currently, a majority of capacitors in electronic products do not contain tantalum but those capacitors, such as niobium-based ones, are commonly larger and have shorter life spans or have reduced capacitance and, in the case of ceramic and aluminium capacitors, are more sensitive to harsh and hot operating conditions (Karhu et al., 2019; Tercero et al., 2018). Therefore, when long-term stability, reliability, size and security matter and when cost is not a primary consideration, for example in automobile anti-lock brake systems, airbag activation systems, satellites, etc., tantalum capacitors remain the only reliable choice (Tercero et al., 2018).

When beryllium is substituted, it always leads to losses in performance. Beryllium is typically used only in applications where properties such as absolute reliability or safety in operation are necessary due to its high price (Tercero et al., 2018; European Commission, 2017b). Alternative materials for copper-beryllium alloys, keeping in mind the performance losses, could include copper nickel silicon alloys, copper iron alloys, copper titanium alloys, copper nickel tin spinodal alloys (Cu-Ni-Sn), phosphor bronzes (Cu-Fe-P) and high performance bronzes (Cu-Pb-Sn + Al/Fe/Mn) (BeST, 2016a).

A summary of potential element to element critical raw material substitution solutions for printed circuit boards are show in Table 7.2.

Table 7.2 Potential substitutes for critical raw materials in printed circuit boards

Component	Critical raw material	From	Substitutes
Light-emitting diodes (LEDs)	Indium Gallium Germanium Iridium Yttrium	Gallium arsenide, gallium nitride	Gallium: liquid crystals made from organic compounds Gallium arsenides, gallium nitride: silicon or silicon-based substrates such as silicon germanium
Transistors	Germanium Silicon Bismuth	Silicon germanium	Germanium: silicon

Capacitors	Palladium Baryte Tantalum		Palladium: other platinum group metals, gold or base metals Tantalum: niobium-based, ceramic, aluminium capacitors
Diodes	Gallium Indium Bismuth	Gallium arsenides	Gallium: indium phosphide components (laser diodes, specific wavelengths)
Integrated circuits	Gallium Silicon		Gallium: no effective substitute
Connections	Palladium Platinum	Metal	Gold, nickel, copper, silver

Source: Karhu et al. (2019)

7.4.2 Secondary raw material

Even though waste electrical and electronic equipment and especially printed circuit boards from high tech appliances such as laptops and mobile phones could be a potential secondary raw material source of critical raw materials, currently, besides platinum group metals, the recovery of critical raw materials is very limited/minimal (Ueberschaar et al., 2017). Platinum group metals in printed circuit boards are recovered and recycled as it is economically viable and the recycling infrastructure is in place, whereas for other elements discussed earlier in this section are mainly lost due to their dispersed use (EC, 2018).

Recycling is an important source of platinum group metals. The efficiency of recycling depends greatly on the waste type and on the region. For example, closed loop recycling can be highly effective whereas open loop recycling from so called old scrap is highly dependent on many factors including the palladium price and collection efficiency of end-of-life products (European Commission, 2017b).

As gallium is used only in some applications in very small mass fractions, it is usually further diluted and subsequently lost in the general recycling process. Looking forward, it is not expected that gallium recycling from post-consumer waste will occur on the short or middle term. However, gallium can be recovered from high concentrate fractions which may occur in processing residues from gallium arsenides wafer production (Ueberschaar et al., 2017).

At the moment, tantalum recycling from post-consumer waste, such as waste electrical and electronic equipment, does not occur. Industrial-scale tantalum recycling is commonly based on high purity production scrap, which can be treated using mechanical and hydrometallurgical processes (Ueberschaar et al., 2017).

Beryllium is not currently recycled from post-consumer waste as it is used in very low quantities and further dilutes in treatment. Beryllium can be recovered from production alloy scrap as it is attractive from an economic and energy point of view (BeST, 2016b).

7.4.3 Environmental impacts

Gold, nickel and copper are possible alternatives to palladium in electronics. None of them, however, scores significantly better in terms of environmental risk (Table 7.3) as there are an equal or larger number of high environmental risks associated to the mining of these materials. Nevertheless, in terms of the environmental footprint, the production of nickel and copper has a much lower impact on climate change, cumulative energy demand, human toxicity, terrestrial acidification and freshwater eutrophication (Nuss and Eckelman, 2014). The impact of gold, on the other hand, is much higher than that of palladium for all measures. Platinum, another possible substitute of palladium, also has a significantly higher environmental impact (Nuss and Eckelman, 2014). As the substitution of palladium with nickel or copper likely results in performance losses, the environmental impact needs to be compared at the level of the end application to make sure that the gains in the production of raw materials are not nullified by increased impacts in other parts of the application's lifecycle.

Gallium in semiconductors could be substituted with silicon. This can lead to environmental improvements, as silicon mining and processing has fewer medium and high risks, especially in terms of pollution at the mining site. The environmental impact of silicon production is also substantially lower for all five indicators considered – climate change, cumulative energy demand, human toxicity, terrestrial acidification and freshwater eutrophication. However, as significant performance and efficiency losses can be expected, the effects over the entire lifecycle of the end application need to be evaluated.

Table 7.3. Evaluation of the environmental hazard potential of substitutes for critical raw materials in electronics ([72])

	Goal	Indicator	Nickel	Gold	Copper	Silicon
			Sulawesi, Indonesia	Chang Shan Hao, China	Escondida, Chile	Jiangsu, China
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Siderophilic element in laterite	Siderophilic element, both oxide and sulphide zones in deposit	Chalcophilic element	Lithophylic element
		Paragenesis with heavy metals	Nickel has toxic properties and is often associated with heavy metals	Au is associated with copper, lead, zinc and arsenic	Copper has toxic properties and is often associated with heavy metals	No indications that silicon is associated with heavy metals
		Paragenesis with radioactive components	No indications that nickel is associated with elevated levels of uranium and thorium	No indications that gold is associated with elevated levels of uranium and thorium	No indications that copper is associated with elevated levels of uranium and thorium	No indications that silicon is associated with elevated levels of uranium and thorium
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Open pit	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Pyro-metallurgy and acid leaching	Heap leaching, commonly with cyanide solution	Froth flotation (incl. toxic chemicals) and acid leaching	Produced in electric arc furnace

[72] The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

	Goal	Indicator	Nickel	Gold	Copper	Silicon
			Sulawesi, Indonesia	Chang Shan Hao, China	Escondida, Chile	Jiangsu, China
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	Indonesia: high natural accident hazard	China: high natural accident hazard	Chile: medium natural accident hazard	China: high natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	High water stress	High water stress	High water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	Within Feruhumpenai – Matano AZE site	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	Indonesia: medium EPI	China: medium EPI	Chile: medium EPI	China: medium EPI

Source: evaluation framework based on Manhart et al., 2019, natural accident hazard: GAR Atlas Risk Data platform ([73]), Water Stress Index: Pfister, 2011; Sonderegger et al., 2015, protected areas: ProtectedPlanet 2014-2020 ([74]), AZE sites: 2018 - 2020 American Bird Conservancy ([75]), value chain: Nuss and Eckelman (2014), Ecoinvent v2.2 (2010), nickel: PorterGeo Database ([76]), Australian Trade and Investment Commission ([77]), gold: Ferro and Saccone, 2008; Dehoust et al., 2017, PorterGeo Database ([78]), Geosystems International ([79]), SGS ([80]), copper: Luszczkiewicz, Chmielewski and Konieczny, 2012; Dehoust et al., 2017, MiningTechnology ([81]), silicon: Ferro and Saccone, 2008; Boussaa et al., 2016, WorldAtlas ([82])

Secondary raw materials

As for all applications, using recycled critical raw materials to produce electronics can result in large environmental savings. For the recycled material input, the risks related to mining are eliminated. Furthermore, the energy needed to produce recycled metals is typically 60–95 % less than that needed to produce primary metals, resulting in lower environmental impacts (Norgate, 2013).

[73] https://risk.preventionweb.net/
[74] https://www.protectedplanet.net/
[75] https://zeroextinction.org/site-identification/2018-global-aze-map/
[76] http://www.portergeo.com.au/database/mineinfo.asp?mineid=mn166
[77] https://www.austrade.gov.au/ArticleDocuments/1406/PT VALE INDONESIA TBK_JUL18_web.pdf.aspx
[78] http://www.portergeo.com.au/database/mineinfo.asp?mineid=mn1290
[79] http://www.geosysint.com/projects/change-shan-hao/
[80] https://www.sgs.com/en/mining/metallurgy-and-process-design/cyanidation-technologies/cyanide-leaching
[81] https://www.mining-technology.com/projects/escondida/
[82] https://www.worldatlas.com/articles/top-15-quartz-exporting-countries.html

8 Conclusions

8.1 Substitution of critical raw materials in applications

Critical raw materials are important in many technologies which are vital to addressing the challenges society is currently facing, for example in mitigating climate change or digitalising future industry/society. In these technologies, critical raw materials provide unique properties to many materials and components, which, for example, enable more efficient and reliable performance. The use of critical raw materials in different applications varies significantly, while in magnets and batteries they can constitute tens of per cent of the composition, in alloys and electronics concentrations are usually low.

Element to element substitution of critical raw materials is difficult in many applications and losses in performance or reliability are often expected. In addition, when substituting a material in an application, the design of the component will in many cases change, and may affect the design of the whole end product. Due to the different properties and/or design of the end product, the environmental impacts of different critical raw materials and their substitutes are challenging to compare. Typically, the development of a substitution solution is driven by performance and functionality criteria, as well as the reduction of the costs and supply risk, rather than the environmental aspects.

For some critical raw materials, such as phosphorus used in mineral fertilisers, element to element substitution is not possible at all although, in this case, secondary raw materials could support the supply. In fact, the recycling of many critical raw materials from post-consumer waste/scrap is negligible at the moment for various reasons such as low concentrations in end products, a lack of infrastructure to support recycling, and with price fluctuations of critical raw material.

8.2 Environmental risks and impacts of critical raw materials

8.2.1 Environmental risks

Categories of environmental risks

Table 8.1 summarizes the main environmental risks associated with the mining, extraction, refining and production stages of those critical raw materials that are essential for providing functionality to the applications that were selected for this analysis. The environmental hazard ([83]) potential used to evaluate risks, indicates how likely it is that environmental impacts will occur if no appropriate countermeasures are taken.

- An important category of such risks is related to the specific **mineralogical and geological characteristics** of the extraction site. These conditions generate particular, local pollution risks that should be monitored and controlled locally, since natural characteristics cannot be circumvented. An example are those critical raw materials that are typically present in nature in association with radioactive elements, such as uranium and thorium. This is often the case for beryllium, rare-earth elements, phosphates and tantalum. In an analogue way, some critical raw materials – such as boron, cobalt, gallium, palladium and tungsten – are generally found in the presence of heavy metals that are toxic to humans and the natural environment when released during extraction. Finally, the oxidation of sulphide minerals will inevitably lead to the generation of acid waters that might pollute ground and surface waters if not properly managed. Conditions for the formation of acid waters are present in, for example, one of the largest palladium mines in the world.

[83] An environmental hazard is an event that has the potential to cause environmental impacts

- A second category of environmental risks associated with critical raw materials is related to the effects of the use of particular **mining and extraction technologies and processes**. These on-site, process-bound risks are difficult to avoid, since most of such processes are highly material-specific, and thus, to limit the direct impacts on local ecosystems, require the implementation of appropriate measures to monitor and control pollution. Most often, critical raw material mining methods present medium risks to vegetation, and effects on groundwater levels or land use from mining and stockpile deposition. The use of toxic reagents and other auxiliary substances in the extraction process, however, leads to high environmental risks in the extraction of beryllium, niobium, palladium and rare-earth elements.

- The third category of risks are those risks that are not specific to the mineralogical nature of the critical material, nor to the particular mining and extraction techniques, but rather to the **natural environment** and **conditions** at the location where mining and extraction activities take place. These risks can be avoided by limiting the establishment of mines in the most sensitive areas, and by the implementation of adequate permitting procedures and monitoring systems. Most countries have established protected areas for the preservation of their most valuable national ecosystems, in which mining activities are not allowed. Critical raw materials that are typically found in areas where water is scarce include beryllium, boron and silicon. Most of world's critical raw material mining areas, with the exception of some major cobalt and tantalum mining sites, are prone to natural disasters such as flooding, earthquakes, storms and landslides. Where such risks are present, their environmental effects should in all cases be managed by applying site-specific prevention plans and emergency procedures.

- It was stressed that critical raw material environmental risk management requires putting measures for monitoring and control in place, the establishment of rigorous permitting procedures to avoid local pollution and ecosystem destruction, as well as the implementation of adequate, site-specific prevention and emergency plans. To achieve the development, and then subsequent and continued enforcement of such risk management procedures, efficient and effective **local and national governance** systems are required. For most critical raw materials, unfortunately, the corresponding mining and extraction activities are developed in countries with a medium to poor environmental performance. This is particularly the case for cobalt and tantalum. Additionally, it is evident that insufficient management and control of site-specific environmental risks often result in actual, local pollution and ecosystem destruction, putting considerable pressure on local communities and their social and economic subsistence.

Table 8.1 Summary of the environmental hazard potential of the main critical raw materials in applications ([84])

		Critical raw material	Beryllium	Rare-earth elements	Palladium	Cobalt	Phosphate	Boron	Gallium	Tantalum	Silicon	Niobium	Tungsten	Vanadium	Magnesium	Natural graphite
		Application	Electronics	Magnets, batteries	Electronics	Magnets, batteries	Fertilisers	Magnets, fertilisers	Electronics	Electronics	Alloys	Alloys	Alloys	Alloys	Alloys	Batteries
	Goal	**Indicator**														
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	green	green	red	yellow	yellow	green	green	green	green	green	yellow	green	green	green
Geology		Paragenesis with heavy metals	yellow	yellow	red	red	yellow	red	red	green	green	yellow	red	yellow	green	green
Geology		Paragenesis with radioactive components	red	red	yellow	yellow	red	green	yellow	red	green	yellow	green	green	green	green
Technology	Limiting the direct impacts on ecosystems	Mining method	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
Technology	Avoiding pollution risks	Use of auxiliary substances	red	red	red	yellow	yellow	yellow	yellow	green	green	red	yellow	green	green	yellow
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	red	red	yellow	green	red	yellow	red	green	red	yellow	yellow	red	red	red
Natural environment	Avoiding competition in water usage	Water Stress Index	red	green	green	green	green	red	green	green	red	green	green	yellow	green	green
Natural environment	Protection of valuable ecosystems	Protected areas and AZE sites	yellow	green	green	yellow	green	green	green	yellow	green	green	green	green	green	green
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	green	yellow	yellow	red	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow

[84] This table is based on one major mining site per critical raw material. The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

Country environmental risk management performance

As explained in the previous section, the environmental risks associated with the mining and production of raw materials have the potential to cause severe, but geographically confined environmental burdens, mainly or exclusively affecting local ecosystems, and the quality of life of workers and resident populations. In general, these risks are monitored and managed in accordance with the legal framework for environmental protection and pollution prevention in the country of production. This means that in countries with weak legal frameworks, poor environmental standards or in which enforcement is not effective, the potential of raw material producing activities to damage human health and ecosystems will likely be higher compared to countries with a mature and solid legal system for environmental protection. This means that the extraction and processing of critical raw materials with similar mineralogies, under comparable natural conditions and using the same technological processes will lead to very divergent environmental impacts in different countries, depending on the environmental risk management schemes in place.

To illustrate the different levels of risk management (Figure 8-1) the largest supplier to the EU of each of the selected critical raw materials is shown, together with its overall Environmental Performance Index score and the score for fine particulate matter ($PM_{2.5}$) exposure ([85]). In several cases, for instance for cobalt and silicon metal, the largest EU supplier is not the major production country shown in Table 8.1.

The fine particulate matter exposure metric was selected here, since fine dust generation has considerable local impacts on human health, of both workers and local residents, and is, at the same time, easily linkable to mining operations and related activities such as the storage and disposal of tailings (Petavratzi et al., 2005). It is observed that in all countries with an Environmental Performance Index score close to or below 50, $PM_{2.5}$ scores are worse (Figure 8-1).

[85] $PM_{2.5}$ exposure was measured using the number of age-standardized disability-adjusted life-years lost per 100,000 persons (DALY rate) due to exposure to fine air particulate matter smaller than 2.5 micrometers (PM2.5). A score of 100 indicates a country has among the lowest DALY rates in the world (≤1st-percentile), while a score of 0 indicates a country is among the highest (≥99th-percentile). Data for this indicator come from the Institute for Health Metrics & Evaluation's (IHME) Global Burden of Disease (GBD) study. (From: https://epi.yale.edu/epi-results/2020/component/pmd)

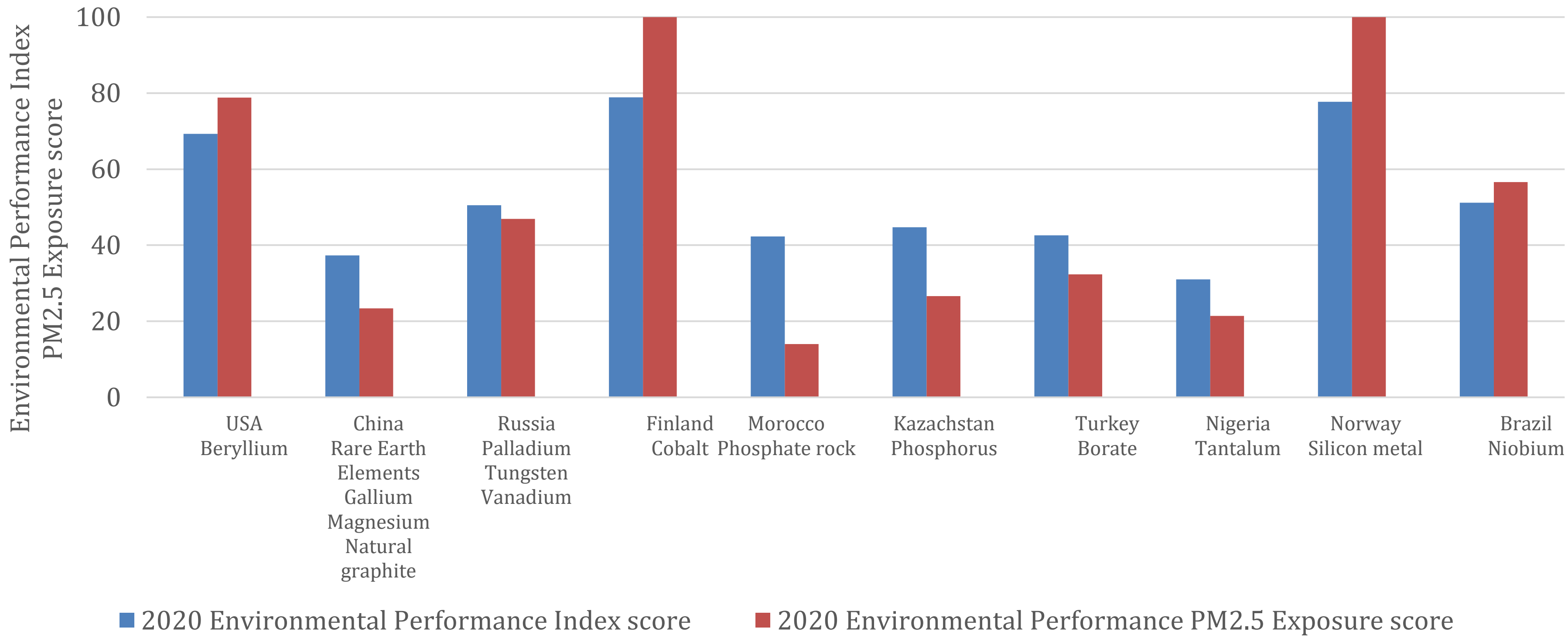

Figure 8-1. Largest supplier of critical raw materials to the EU (2017) and overall Environmental Performance Index score and the score for $PM_{2.5}$ exposure (2020) ([86])

[86] Largest suppliers of critical raw materials to the EU in 2017 were obtained from https://rmis.jrc.ec.europa.eu/?page=why-crms-have-a-supply-risk-8e8af9; Environmental Performance scores from https://epi.yale.edu/. For beryllium and palladium the analysis of the EU sourcing excluded beryllium and palladium, among others, due to little or no EU sourcing activity. For these critical raw materials, main global suppliers are presented here, respectively the United States and Russia. It should be noted that Congo Democratic Republic has replaced Finland as the main source of cobalt for EU in the 2020 list of critical raw materials, among other changes.

Policy recommendations on environmental risks management

To reduce the environmental risks associated with critical raw materials, **sourcing practices** that present significant and well-known pollution risks derived from geological conditions, such as paragenesis with heavy metals and radioactive components, or from the use of auxiliary substances (Table 8.1), should carefully consider the prevention and mitigation measures applied in the country of origin. The existence of adequate emergency and risk management plans should be checked for mining and processing facilities that are prone to suffer from natural catastrophes, such as floods, earthquakes, storms and landslides. Competition for water usage might be an issue at several locations, particularly for beryllium, borates, silicon metal and vanadium, and should be monitored accordingly.

Risks, such as (eco)toxicity and carcinogenicity, that are **inherent to the nature and chemistry of the selected critical raw materials** − and of the related substances that include these critical materials − should be taken into consideration at production and processing sites. Proper management of these types of risk must also be observed over the entire supply chain by the mining operators and the processors of the hazardous critical material or related substances in the manufacture of the final product.

Cobalt, for instance, has recognized genotoxic and cancerogenic properties. Hexavalent chromium compounds are especially toxic to humans. Beryllium is highly toxic if inhaled in dust form, leading to berylliosis. (European Commission, 2014)

The EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC Regulation No. 1907/2006) controls the production, import and use of chemical substances and aims, among other things, to ensure a high level of protection of human health and the environment from the risks that can be posed by chemicals. REACH considers a Substances of Very High Concern (SVHC) candidate list that includes substances related to critical raw materials that might be subject to authorisation requirements. Many of them are linked to critical raw materials, as shown in Table 8.2 (Chapman et al., 2013). Most are included due to being classified carcinogenic and/or toxic to reproduction.

Table 8.2 Substances of Very High Concern related to critical raw materials.

Materials	Count	Substances on the SVHC Candidate List
Antimony	1	Pyrochlore (antimony lead yellow)
Borates	5	Diboron trioxide, Tetraboron disodium heptaoxide(hydrate), Boric acid, Disodium tetraborate, Lead bis(tetrafluoroborate)
Chromium	12	Dichromium tris(chromate), Pentazinc chromate octahydroxide, Potassium hydroxyoctaoxodizincatedichromate, Chromic acid and Dichromic acid (and oligomers), Chromium trioxide, Ammonium dichromate, Sodium chromate, Potassium chromate, Lead sulfochromate yellow (C.I. Pigment Yellow 34), Lead chromate, Sodium dichromate, Lead chromate molybdate sulphate red (C.I. Pigment Red 104)
Cobalt	5	Cobalt dichloride, Cobalt(II) diacetate, Cobalt(II) sulphate, Cobalt(II) carbonate, Cobalt(II) dinitrate
Fluorspar	7	Ammonium pentadecafluorooctanoate (APFO), Pentadecafluorooctanoic acid (PFOA), Henicosafluoroundecanoic acid, Lead bis(tetrafluoroborate), Heptacosafluoro-tetradecanoic acid, Tricosafluorododecanoic acid, Pentacosafluorotridecanoic acid
Phosphate rock	2	Trilead dioxide phosphonate, Tris(2-chloroethyl)phosphate
Silicon	2	Zirconia Aluminosilicate Refractory Ceramic Fibres, Aluminosilicate Refractory Ceramic Fibres

Element or substance related risks are managed by strictly observing **national and international standards and regulations** applicable to the production, use, transport and trade of hazardous substances.

8.2.2 Environmental impacts

Section 8.2.1 summarised different categories of environmental risks associated to the mining and extraction. Such risks are typically both mineral and site specific, and must be managed as well as possible to avoid the risk being converted into a real impact. At the same time, it is also relevant to consider the environmental impacts that are effectively produced along different stages of the complete critical raw materials' production chain. Commonly, different categories of impacts are considered. Such impacts always refer to direct and indirect global effects. An example of an indirect effect is the carbon dioxide emissions generated during the extraction and refining of oil needed to provide the fuel for the production of a chemical reagent that is used to extract a particular critical raw material from the mined ore. These carbon dioxide emissions probably occur far from the critical raw material's mining site.

Global, full value chain environmental impacts of the analysed critical raw materials that are essential for the selected applications are presented in Table 8.3.

Table 8.3. Summary of the environmental impact in the value chain of the main critical raw materials in the selected applications ([87])

	Application	Magnets			Batteries			Alloys					Fertilisers		Electronics			
	Environmental impact indicator	Rare-earth element	Cobalt	Boron	Rare-earth element	Cobalt	Natural graphite	Magnesium	Niobium	Vanadium	Silicon	Tungsten	Phosphate	Boron	Palladium	Tantalum	Beryllium	Gallium
Value chain	Carbon footprint (kton CO_2-eq/application)																	
	Cumulative energy demand ([88]) (TJ/application)																	
	Human toxicity, cancer and non-cancer (CTUh/application)																	
	Terrestrial acidification (kton SO_2-eq/application)																	
	Freshwater eutrophication (kton P-eq/application)																	

[87] Estimated relative impact based on life cycle assessment (Nuss and Eckelman, 2014; Ecoinvent v2.2, 2010). The colour scale indicates the magnitude of the environmental impact: green represents a low, yellow a medium and red a high impact.We consider the impact to be low if it is below the 25 % quantile of all results for the evaluated material in their application, and high if it is above the 75 % quantile.

[88] The cumulative energy demand is not an environmental impact as such; however, it is directly related to many environmental impacts generated by the use of (mainly fossil) energy throughout the lifecycle.

Particularly high global environmental impacts can be observed for those critical raw materials that are essential for producing functional metal alloys and those that are needed for agricultural fertilisers. The magnitude of the individual impacts of a material in an application is the result of the combination of the environmental impact relative to the production of one tonne of the material on the one hand, and, on the other, the number of tonnes of that are required for the global production of the particular application.

For some critical raw materials, the elevated environmental impact is thus mainly due to the high volume that is required for the application, even when the impacts of the production of one tonne of the respective material are relatively low, as is the case for magnesium in metal alloys and for phosphates in fertilisers. Other critical raw materials present significant per tonne impacts but are required in very low volumes to provide the desired functionality to the selected application. This is, for instance, the case for gallium used in electronics. Another example is the mining and extraction of borates, which have a very low environmental impact per tonne but show medium total impacts when used massively in fertiliser applications. At the same time, the total environmental impact attributable to the use of boron in magnets is low. Similarly, the impact of cobalt in magnet applications is low compared to its application in batteries.

From Table 8.3 it can be further observed that for most critical raw materials and impact categories, the level of environmental impacts attributable to a particular material application is very similar in the different impact categories, except for the category of human toxicity, and for the vanadium and tungsten applied in metal alloys. Both vanadium and tungsten have low freshwater eutrophication impacts, but at the same time present elevated impacts due to, respectively, the high energy consumption of the vanadium production processes, and human toxicity and terrestrial acidification impacts associated to tungsten mining.

Lifecycle environmental impacts of critical raw materials' mining and processing include both local and global, and direct and indirect effects that are a consequence of the resource use and the generation of waste and emissions over the production process. The underlying data used for calculating these effects represent global averages of process parameters such as resource consumption and emissions. These values do often not allow the distinguishing of local geographical and natural conditions, or of site-specific process optimisations and management measures in place. It is thus possible that the environmental impacts as calculated by life cycle assessment methodologies, deviate, for better or for worse, from the actual impacts of a specific mining or processing operation at a certain location.

Environmental impact calculations however enable the identification of environmental hotspots of production processes, since they distinguish a series of different environmental impact categories, such as damage to human health, ecosystems and resource availability (Figure 8-2).

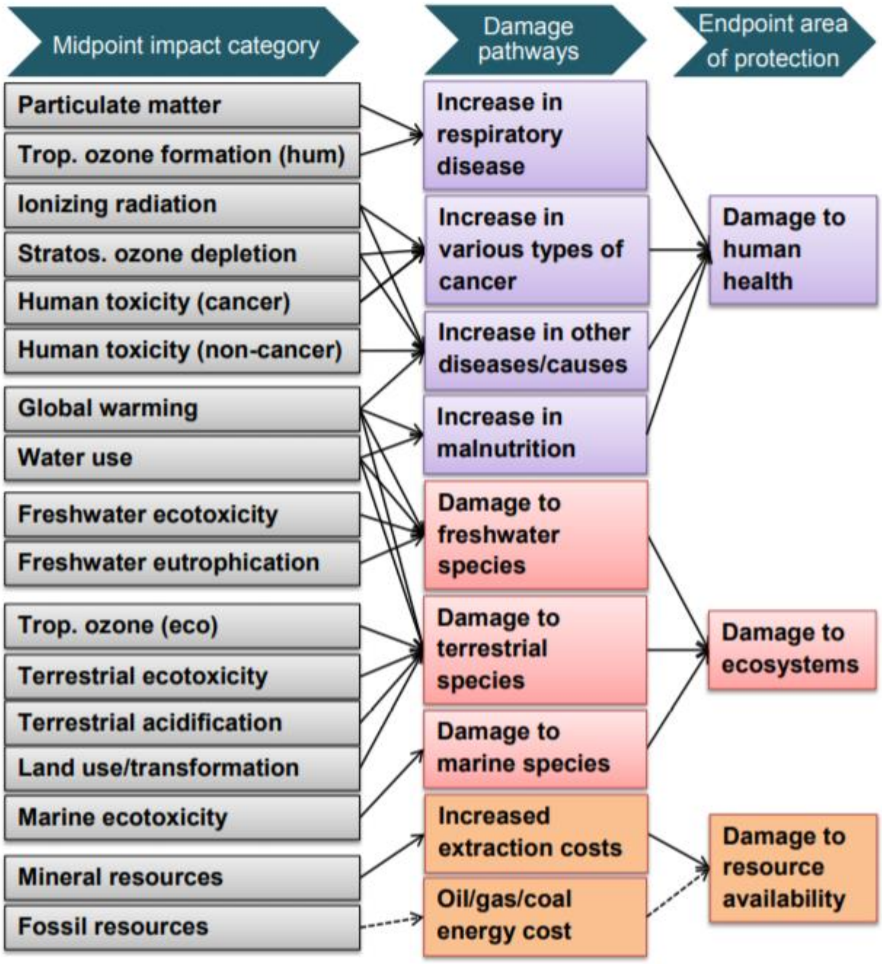

Figure 8-2 Different environmental impact categories[89]

Source: Huijbregts et al., 2016

In general, since the mining and processing of minerals is usually very energy intensive, a considerable share of the environmental impacts can be associated to the use of energy. For this reason, Table 8.2 considered the cumulative energy demand (CED) as a relevant additional parameter and screening indicator for assessing environmental impacts of critical raw materials production.

The environmental impacts calculations as presented in Table 8.2 should thus be used as a tool to identify the particular impact categories that are contributing most to the global environmental effects associated to the production of the critical raw materials that are essential for providing specific functions to the selected applications. Site-, process- or installation-specific efforts to improve the critical raw materials' environmental performance should preferably focus on the reduction of energy use, resource consumption, and the generation of emissions and waste that were found to account for a relevant share of the impacts.

[89] In the diagram, '*Trop. ozone formation (hum)*' refers to the impacts of tropospheric ozone formation on human health; '*Stratos. ozone depletion*' refers to stratospheric ozone depletion; '*Trop. ozone (eco)*' refers to the impacts of tropospheric ozone formation on terrestrial ecosystems.

8.3 Application-specific outcomes

Magnets

Neodymium-iron-boron magnets are the most important permanent magnet type for high-tech applications such as wind turbines and electric vehicles. Neodymium and praseodymium are the most important critical raw materials in these magnets, in addition dysprosium and terbium are used in high temperature applications. In the European Commission's assessment of critical raw materials for Europe, magnets are important applications in terms of economics providing over half of the economic importance for dysprosium, gadolinium, neodymium and samarium. When looking towards the future, the growth of wind power and vehicle electrification is expected to increase the demand especially for dysprosium, neodymium and praseodymium.

The use particularly of rare-earth elements, boron and cobalt in the production of magnets is associated with considerable environmental impacts. Most of these impacts are generated locally at the mining sites, often located in countries with medium or poor environmental performance. The mining and refining processes of rare-earth elements are energy intensive and associated with heavy metal and radioactive emissions. Cobalt mining and refining also mainly affects local communities, causing environmental as well as social and health related burdens. Cobalt refining often uses coal as its main energy source. Borate mining operations can be a source of local arsenic pollution.

The environmental impact of the critical raw materials in magnets used in electric vehicles is very small compared to the total impact over the vehicle's lifetime, including both production and use. Moreover, in ideal conditions, the lifecycle climate change impact of an electric vehicle is about a third of that of a combustion engine vehicle, whereas in other impact categories, such as human toxicity and freshwater ecotoxicity, internal combustion vehicles might perform better than their electric counterparts. In an analogue way, the neodymium-iron-boron magnet in wind energy generators represents only a small share of the total wind turbine production impacts and saves material resources such as steel and composites. From a lifecycle perspective that takes into account the energy production, the use of neodymium in the wind turbine might, however, lead to higher impacts in the category of resource depletion as compared to equivalent fossil-based energy generation.

Substitution solutions exist on various levels. Direct element-to-element substitution for critical raw materials in magnets with non-critical ones do not exist but two possible routes can be applied to reduce the amount of critical raw materials in neodymium-iron-boron magnets: first, by the (partial) substitution of neodymium and praseodymium, and second, using critical raw material-free, alternative magnet technologies. Partial substitution of neodymium and dysprosium with other critical raw materials – cerium, cobalt and lanthanum – could take place. When considering magnet technologies, ferrite magnets are assumed to be the most promising candidates to substitute neodymium-iron-boron magnets in electric vehicle motors, but, electromagnets have also gained attention. Some of the rare-earth element-free motors are able to achieve similar performance, however there are also weaknesses and construction/design changes that need to be taken into account. No commercial rare-earth element recycling of consumer magnet applications is expected to increase the supply of critical raw materials in near future.

From the environmental point of view, some substitute magnet technologies applicable in electric vehicles appear to have lower efficiencies than neodymium-iron-boron magnets, which may result in a higher overall impact of the application, even if the impact of the manufacture of the magnets or the alternative systems is lower. On the other hand, if higher efficiency can be achieved without critical raw materials in the magnets, this will probably result in an overall lower environmental impact of the substitute. This has been found to be the case for an electric vehicle motor design with ferrite magnets, which have a lower impact than a design using neodymium-iron-boron magnets. The replacement of permanent magnet generators by copper-wound rotors was found to increase environmental impacts due to the high energy intensity of copper. The recycling of magnets lowers all impacts as compared to the substituted virgin materials production.

Batteries

Today, lithium ion batteries are the primary battery choice for both consumer electronics and electric vehicles, whereas nickel metal hydride batteries have a minor market share. Critical raw materials, namely cobalt and natural graphite, are key elements in manufacturing of battery electrodes. The development of nickel rich cathode materials has reduced the cobalt content per battery, and synthetic graphite has increased its market share in anode materials especially in applications where high purity is required. In the European Commission's assessment of critical raw materials for Europe, batteries are found to be relevant applications in terms of economic importance for cobalt with a share of 30 %. However, it should be noted that during the assessment in 2017, battery demand was still somewhat modest. It is expected that a significant increase in demand for cobalt and natural graphite will occur as the battery industry evolves. Increasing use of artificial graphite might affect the future demand for natural graphite, though.

The use of critical raw materials, particularly rare-earth elements, cobalt and natural graphite, in the production of batteries is associated with considerable environmental impacts. Graphite mining generates local pollution of groundwater and soil, as well as health impacts from airborne graphite dust. Furthermore, coal-based energy is often used for natural graphite purification and surface modification.

A relevant portion of the environmental impacts of battery production are due to the extraction and refining of cathode materials, particularly of cobalt and nickel. The total environmental impacts of battery production, however, depend heavily on the region from where the materials are sourced and in which the battery is produced. The environmental impact of natural graphite in the anode is small, and lower than that of synthetic graphite. When batteries are embedded in an end use application, such as an electric vehicle, the contribution of cobalt and other critical raw materials to the total environmental impact of the end use application is relatively limited, since the impact of an electric vehicle is largely due to the electricity used during its operation. At the same time, batteries can help achieve a greater share of renewable energy, by enabling the balancing of supply with demand, with the corresponding environmental benefits.

Substitution of critical raw materials is not the only driver for seeking alternative materials for lithium-ion batteries, but the insufficient capacity, high cost and safety of current commercial electrode materials act also as drivers for their replacement. The currently existing material combinations almost exclusively employ critical raw materials on at least one electrode. It has been assumed, however, that in the short term sodium-ion and lithium-sulphur battery technologies are the best candidates to reach sufficient technology maturity for their wider commercial deployment and the substitution of lithium-ion batteries. Hydrogen is often considered a very capable future energy-storage and energy-transport medium. However, due to the limitations related to its storage and the considerable investment that is needed to establish distribution infrastructure, researchers are working on concepts for the storage and transport of hydrogen in, for example, chemically bound forms.

None of the proposed substitution solutions seem to target or produce a reduction in those environmental impacts associated with the critical raw materials that are currently used. Furthermore, the existing industrial recycling processes are only capable of recovering materials that require resource-intensive processing before they can be reused in battery production. Nevertheless, using recycled materials could help to substantially reduce the environmental impacts of electrode production.

Alloys

Critical raw materials are used in several high-strength and low-weight alloys in the automotive industry. The most important ones in terms of volume are magnesium used in aluminium alloys and niobium and vanadium used in high-strength low alloy and advanced high-strength steels. In addition, beryllium, cobalt, silicon and tungsten are found in alloys in cars. In the European Commission's assessment of critical raw materials for Europe metal alloys are essential in term of economic importance for so called refractory metals such as magnesium, niobium, tungsten and vanadium. The heavy consumption in the transport sector generates the economic importance. In the future, a modest increase in critical raw material demand is expected due to the manufacture of lighter vehicles in order to reduce environmental impacts.

When looking at the environmental aspects, niobium and tungsten have a high local pollution risk at their mining sites. Most of the critical raw materials for alloying are produced in countries with medium environmental performance index scores. Magnesium, silicon and vanadium present particularly elevated risks for accident hazards due to floods, earthquakes, storms and landslides. Globally, magnesium extraction and production for alloying has the highest environmental impact, silicon the lowest. However, in alloys with a high silicon weight share, such as some aluminium casting alloys, silicon is among the alloying elements that contribute most to the alloy's total environmental impact.

Element-to-element and material-to-material substitution solutions exist for the critical raw materials in alloys but often result in reduced performance and higher cost, and some of the options are critical raw materials themselves. Advanced composite materials, such as reinforced plastics, are a critical raw material-free alternative for some applications in vehicles. When considering secondary raw material options, functional recycling of critical raw materials from post-consumer scrap is not carried out in practice due to, amongst other things, low concentrations and unknown composition. Commonly critical raw materials are diluted in the recycling process and are lost. However, recycling from new scrap, such as manufacturing residues in which the composition is known, does take place.

The impact on the environment does not seem to be the driver for the substitution of critical raw materials in alloys. Substituting niobium in high-strength steels and stainless steel with molybdenum, tantalum, titanium or vanadium would not significantly decrease the environmental risks. When looking at the environmental impacts over the value chain, an impact reduction of human toxicity and freshwater eutrophication could be achieved by replacing niobium by vanadium. Nevertheless, the carbon footprint, cumulative energy demand and terrestrial acidification impacts would increase, even if similar quantities were used, but the performance would not be affected. As for all applications, using secondary critical raw materials to produce alloys could result in significant environmental savings as the risks related to mining are for example eliminated.

Mineral fertilizer

Critical raw materials used in the production of mineral fertilisers are phosphate rock for phosphate fertilizers, and borate for fertilisers containing boron as a micronutrient. In the European Commission's assessment of critical raw materials for Europe, mineral fertiliser is crucial, especially phosphate rock in terms of economic importance. It is expected that population growth, among other things, will contribute to a modest growth in the demand for fertilizers and consequently the demand of phosphate rock.

The extraction of both phosphate rock and borate minerals presents medium to high environmental risks for most of the indicators used. Additionally, the extensive surface mining operations associated to their extraction probably will affect landscapes and ecosystems close to the mine. Both phosphate and boron are mainly produced in countries with medium environmental performance scores. Borates and phosphate rock are often found in association with arsenic or other heavy metals. Radioactive components might be an issue for phosphate rock extraction. Globally, the process of fertiliser production, especially for phosphate, generates high impacts in the environmental impact categories of carbon footprint, cumulative energy demand, human toxicity, terrestrial acidification and freshwater eutrophication. This is due to the large amount of fertilisers produced worldwide, as the environmental impacts per tonne are limited.

The contribution of the mining stage of phosphate rock and borates to the total environmental impact of the corresponding fertiliser production appears to be relatively small. Fertilisers are applied to agricultural soil, along with possible contaminants, such as heavy metals, in order to allow the production of food and biomass.

Phosphorus and boron are essential nutrients for plant growth and thus cannot be substituted in fertilisers. Phosphorus consumption can, however, be reduced, for example by increasing the efficiency of the food chain, shifting from a phosphorus intensive, meat and dairy based diet to a vegetarian one, and increasing the recovery of phosphorus from secondary sources.

Electronic components

Many different critical raw materials are used in small quantities in electronics, usually to provide special functions such as enabling miniaturisation. Some of the most relevant for electronics are palladium in multilayer ceramic capacitors, gallium in semiconductors, tantalum capacitors and beryllium in copper alloys. Even though electronics utilise several critical raw materials, only a few, beryllium, gallium, and iridium, were found to be truly significant in terms of economic importance according to the European Commission’s assessment on critical raw materials for Europe. New application areas such as automotive electronics and artificial intelligence may increase the future demand for electronics and consequently the related critical raw materials.

Four important critical raw materials used in electronic components, beryllium, gallium, palladium and tantalum present high pollution risks at their respective mining sites. Tantalum is mainly mined in countries with very poor environmental performance scores. The production of all four critical materials, but particularly palladium, is associated with high environmental impacts per tonne. Nevertheless, due to the low concentrations required in electronic components, the global impacts can be qualified as medium to low.

The share of critical raw materials in the total impact of, for example, printed circuit boards is fairly negligible for all impact categories, since only very small quantities are required to produce a functional printed circuit board. The printed circuit boards are embedded in diverse end-use applications, such as laptops, washing machines or large equipment, in which the environmental impact share due to the mining and production of the required critical raw materials remains negligible.

Element-to-element substitution in electronic components often leads to performance losses since they provide unique properties to the components. In many cases, possible substitution elements are used if performance requirements are met, as using critical raw materials is expensive and therefore their use is limited to when they are really necessary. Waste electrical and electronic equipment and especially printed circuit boards, are an interesting and potential supply sources for secondary critical raw materials. For platinum group metals, waste electrical and electronic equipment is currently a significant supply source while for other critical raw materials recycling from post-consumer products does not occur.

Abbreviations

AlNiCo	Aluminium-nickel-cobalt
AHSS	Advanced high-strength steels
AMD	Acid mine drainage
AZE	Alliance for Zero Extinction
BEV	Battery electric vehicles
CO_2	Carbon dioxide
CED	Cumulative energy demand
$CoSO_4$	Cobalt sulphate
CTUh	Comparative toxic unit for humans
D2EHPA	di-(2-ethylhexyl)phosphoric acid
DAP	Diammonium phosphate
DFIG	Doubly-fed induction generator
DRC	Democratic Republic of the Congo
EESG	Electrically excited synchronous generator
EI	Economic importance
EHP	Environmental hazard potential
EPI	Environmental Performance Index
EV	Electric vehicle
FAO	Food and Agriculture Organization of the United Nations
GW	Gigawatt:1 billion (10^{12}) watts
GWh	Gigawatt hours
HDD	Hard-disk drive
HEV	Hybrid electric vehicle
H_2O_2	Hydrogen peroxide
HSLA	High-strength low alloy
H_2SO_4	Sulphuric acid
ICT	Information and communications technology
IFA	International Fertilizer Association
In_2Se_3	Indium selenide
K_2O	Potash
Kton	Kilotonne: 1,000 tonnes
LCA	Lifecycle assessments
LCI	Lifecycle inventory
LCO	Lithium cobalt oxide
LED	Light-emitting diode
LFP	Lithium iron phosphate
LIB	Lithium ion battery
$LiBO_2$	Lithium borate
Li_5FeO_4	Pentalithium ferrite
$LiFePO_4$	Lithium iron phosphate
$LiMn_2O_4$	Lithium manganese oxide
Li_2O_2	Lithium peroxide
$LiPF_6$	Lithium hexafluorophosphate
LiPON	Lithium phosphorus oxynitride
LMO	Lithium manganese oxide
LOHC	Liquid organic hydrogen carrier
LTO	Lithium titanate ($Li_4Ti_5O_{12}$)
MAP	Monoammonium phosphate
MgO-C	Magnesia-carbon
MLCC	Multilayer ceramic capacitors

MMC	Metal matrix composites
MW	Megawatt: 1 million (10^6) watts
NCA	Lithium nickel cobalt aluminium oxide
NdFeB	Neodymium-iron-boron
NiMH	Nickel metal hydride
NiO(OH).	Nickel oxyhydroxide
NMC	Lithium nickel manganese cobalt oxide
O_2	Molecular oxygen/dioxygen
OLED	Organic light-emitting diodes
PCB	Printed circuit board
PHEV	Plug-in hybrid electric vehicle
PMSG	Permanent magnet synchronous generator
$PM_{2.5}$	Particulates with a diameter of less than 2.5 micrometres
PM_{10}	Particulates with a diameter of less than 10 micrometres
PMSM	Permanent magnet synchronous machine
P_2O_5	Phosphate
PSM	Permanent synchronous motor
PVDF	Polyvinylidene fluoride
RAM	Random access module
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFB	Redox flow battery
SI	Substitution index
SmCo	Samarium-cobalt
SnO	Tin oxide
SnO_2	Tin(IV) oxide
SO_2	Sulphur dioxide
Srferrite	strontium-ferrite
SSD	Solid-state disk
SSP	Single superphosphate
SVHC	Substances of very high concern
SynRM	synchronous reluctance machine
Ta_2O_5	Tantalum pentoxide
TBP	Tributyl phosphate
TJ	Terajoule: 1 trillion (10^{12}) joules
TSP	Triple superphosphate
V_2O_5	Vanadium(V) oxide/vanadium pentoxide
WLAN	Wireless local area network
WSI	Water Stress Index

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