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Discussion of the environmental limits of primary raw material extraction and development of a method for assessing the environmental availability of raw materials to further develop the criticality concept (ÖkoRess I)

A method for a raw materials based approach

For our Environment

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Discussion of the environmental limits of primary raw material extraction and development of a method for assessing the environmental availability of raw materials to further develop the criticality concept (ÖkoRess I)

A method for a raw materials based approach

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List of abbreviations

AMD	Acid Mine Drainage
AZE	Alliance for Zero Extinction
BGS	British Geological Survey
CED	cumulative energy demand
CRMD	cumulative raw materials demand
DNEL	Derived No Effect Level
DRI	Disaster Risk Index
EHP	environmental hazard potential
EI	environmental implications
EPI	Environmental Performance Index
GHG	greenhouse gas
GIS	geographic information systems
GSHAP	Global Seismic Hazard Assessment Program
GWP	Global Warming Potential
IBCs	influential boundary conditions
ICMM	International Council on Mining and Metals
IRMA	Initiative for Responsible Mining Assurance
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LOAEL	lowest observed adverse effect level
MRDS	Mineral Resources Data System
NOAEL	no observed adverse effect level
oEHP	overall environmental hazard potential
PBT	persistent, bioaccumulative and toxic
PGA	peak ground acceleration
PGM	platinum group metals
PNEC	predicted no-effect concentration
poEHP	provisional overall environmental hazard potential
ProgRess	German Resource Efficiency Programme
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU regulation)
SAR	structure-activity relationships
UNEP	United Nations Environment Programme
USGS	US Geological Survey
vPvB	very persistent and very bioaccumulative
WDPA	World Database on Protected Areas
WGI	Worldwide Governance Indicator(s)
WRI	World Risk Index
WSI	Water Stress Index

WTA	withdrawal-to-availability (ratio)

1 Introduction

The report presented here, 'Evaluation of the environmental hazard potentials involved in the extraction of abiotic primary raw materials - A methodology for a raw materials based approach', is an interim report of the ÖkoRess I project[1] carried out by the Öko-Institut, ifeu, and Projekt-Consult for the German Environment Agency. It presents the development of a method which can be used to compare abiotic raw materials in terms of their potential environmental impact during extraction and processing.

The following reports have also been compiled and published as part of the ÖkoRess I project[2]:

- 'Discussion of the environmental limits of primary raw material extraction and development of a method for assessing the environmental availability of raw materials for the purpose of further developing the criticality concept' – ÖkoRess I Concept Volume
- 'Evaluation of the environmental hazard potentials involved in the extraction of abiotic primary raw materials – A method for a site-related approach'
- 'Mining residues' (This report does not exist as a German Environment Agency document, but has already been published by the project team as a separate report in the course of ÖkoRess I. [3])

Each individual report is intended to be understandable on its own, so it has been necessary to incorporate some parts of the text into several reports. This applies in particular to the reports on site-related and raw material related evaluation, because the report presented here is a further development of the site-related evaluation method. This further development includes methodological adjustments and additions to the site-related evaluation method. Each of the adjustments and additions is described in one of the sections of this report, in particular in section 4.3, at the beginning of chapter 5, and in chapter 8.

In addition to the reports listed above, the environmental impact of mines has been described in 40 case studies. And the environmental hazard potentials of the mines were assessed using the site-related method mentioned above. The most important case studies have also been published. And the procedure for selecting, describing, and assessing the case studies is described in the OkoRess I Concept Volume.

2 Background

The extraction of abiotic primary raw materials, such as ores, coal, industrial minerals, and building materials, always entails intervention in the natural environment and is often associated with significant environmental impacts. Depending on the type and character of mines, impacts include large-scale reshaping of the natural environment, loss of ecosystems, adverse impacts on the water balance, and pollution of soil, air, and water. However, if one observes the diversity of abiotic raw materials and the methods of extraction and processing, it becomes evident that there can be huge differences in environmental impact, in terms of both magnitude and nature of the impact. These differences are sketched out in the following examples:

- Copper ore, which is mined for the extraction of copper and various associated elements, such as gold and molybdenum, occurs in the form of sulphides and is often associated with

1 Long title: 'Discussion of the environmental limits of primary raw materials extraction and development of a methodology for assessment of the environmental availability of raw materials - for the purpose of further developing the criticality concept', FKZ 3713 93 302

2 The three ÖkoRess I texts are available at: https://www.umweltbundesamt.de/umweltfragen-oekoress

3 Available at: https://www.umweltbundesamt.de/dokument/oekoress-teilbericht-bergbauliche-reststoffe-dr

significant concentrations of heavy metals, such as lead. The storage of mining residues, especially from processing, may therefore lead to auto-oxidation and mobilisation of heavy metals. This effect, which is known as acid mine drainage (AMD), often has a serious impact on groundwater and surface water. Spoil heaps therefore constitute a burdensome legacy which should not be underestimated.

- On the other hand, other ores - such as the aluminium ore bauxite - occur in the form of pure oxides, so that for geochemical reasons there is no potential for auto-oxidation. Bauxite mining is often subject to criticism, however, because of its environmental impact. This is due, among other things, to the fact that bauxite, since it occurs as the surface rock beneath the soil, is always extracted by means of large open-cast mines which are often in very sensitive (tropical) natural areas. In addition, there are other problems associated with the processing of bauxite using the Bayer process, which uses large quantities of caustic soda which are then sometimes dumped with the residues from processing in so-called red mud ponds. As the dam failure in Kolontár, Hungary in 2010 shows, serious incidents can also occur with far-reaching consequences for local inhabitants and the environment downstream.
- The environmental impact of small-scale gold mining is different again. On the one hand, this mining method often extracts deposits which are largely harmless from a geochemical point of view (soap deposits). But the practice of amalgamation with mercury is still widely used and is one of the world's largest sources of emission of this heavy metal which is especially harmful both to the environment and to human health. Another problem is that small-scale gold mining often encroaches on fragile ecosystems and frequently causes damage over large areas. An equally serious problem is the burden of sediment from gold mining carried by rivers and lakes, etc. This often results in serious impoverishment of aquatic ecosystems and also has a negative impact on the quality of drinking water.

The environmental impact of raw materials extraction and attempts to improve the situation are playing an increasingly important role in political debate at the German, European and international levels. This is reflected, among other things, in the German government's Resource Efficiency Programme, "ProgRess", which aims, among other things, to reduce as far as possible "the environmental impacts involved in the extraction of raw materials abroad, such as greenhouse gas emissions, destruction of ecosystems, loss of biodiversity and pollution of soil, water and air"(BMUB 2012). The concrete aims of the programme are defined in the German Resource Efficiency Programme II (BMUB 2016). The following "design approaches" are included among the fields of action for 2016 to 2019, in which action is to be taken to safeguard the sustainable supply of raw materials:

- "Heeding nature conservation and environmental and social issues in the assessment of the criticality of raw materials;
- Supporting projects for the development of methods for the evaluation of the environmental and social sustainability of raw materials extraction."

Assessment methods which promote the inclusion of external costs in cost benefit analyses - as called for in the German government's raw materials strategy (BMWI 2010) - are to be further developed and tested (BMUB 2016).

In this context, it is necessary not only to know about the environmental problems associated specifically with mining and possible counter-measures but also to be aware of which raw materials are especially problematic from an environmental point of view.

3 Existing approaches to the assessment of environmental impacts arising from the global extraction of raw materials

The environmental impacts associated with mining and raw materials have already been investigated at a great many individual sites. In some cases these impacts have been described in depth and in great detail (see, for example: Durand 2012; Kuenzer et al. 2006; Salomons 1995). However, a standardised method of recording for the purposes of assessment has yet to be developed due to the great diversity of abiotic raw materials (outlined earlier) and the frequent difficulty of measuring tangible impacts. Nevertheless, there are methods of assessment which can be used to assess specific environmental impacts and compare raw materials accordingly. These methods are presented briefly in the following subsections.

3.1 Toxicological assessment

Raw materials can be assessed according to their toxicological profile. This is particularly relevant not only for raw materials which are themselves toxic (e.g. heavy metals such as lead, cadmium, and mercury), but also for raw materials which are combined (in their deposits) with relatively high concentrations of toxic substances.

Toxicological assessments are carried out in order to evaluate the risks to human health posed by particular substances. The risk is calculated on the basis of an assessment of both the level of risk (determined by experimental investigation) and an estimation of the harmful effects of exposure. Toxicological assessments are generally carried out using experiments on animals (in vivo) or cell cultures (in vitro) or on the basis of structure-activity relationships (SAR) using different dosages and concentrations. Tests are then carried out to determine whether or not a substance has any harmful effects and, if so, what the relationship is between dosage and effect (Bundesinstitut für Risikobewertung):

- What is the highest dose at which there is no toxic effect? Technical term: NOAEL, "no observed adverse effect level".
- What is the lowest dose at which there is an observed toxic effect? Technical term: LOAEL, "lowest observed adverse effect level"
- What does the dose-response curve look like? And in particular how steep is it?

There is an effect which is harmful to health only when a particular dose (threshold value) is exceeded; Exposure below this level is harmless. It is possible to derive safe limits for substances which are harmful only at dosages above such a threshold. The EU chemicals regulation, REACH, sets threshold levels for certain substances in relation to human health (DNELs, "derived no effect level") and the environment (PNECs, "predicted no effect level"), which may not be exceeded if a chemical is to be authorised.

In the case of certain effects, e.g. the development of cancer, it is not possible to determine a threshold below which a particular substance has no harmful effects. The same applies to substances which are classified as persistent, bioaccumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB) according to REACH.

When considering abiotic raw materials in terms of toxicity, it is important to note that, so far, not all raw materials (rare earth elements, for example) have been investigated sufficiently. Comprehensive data exists on the human and environmental toxicity of most metals. But these data are insufficient for our present discussion for two reasons:

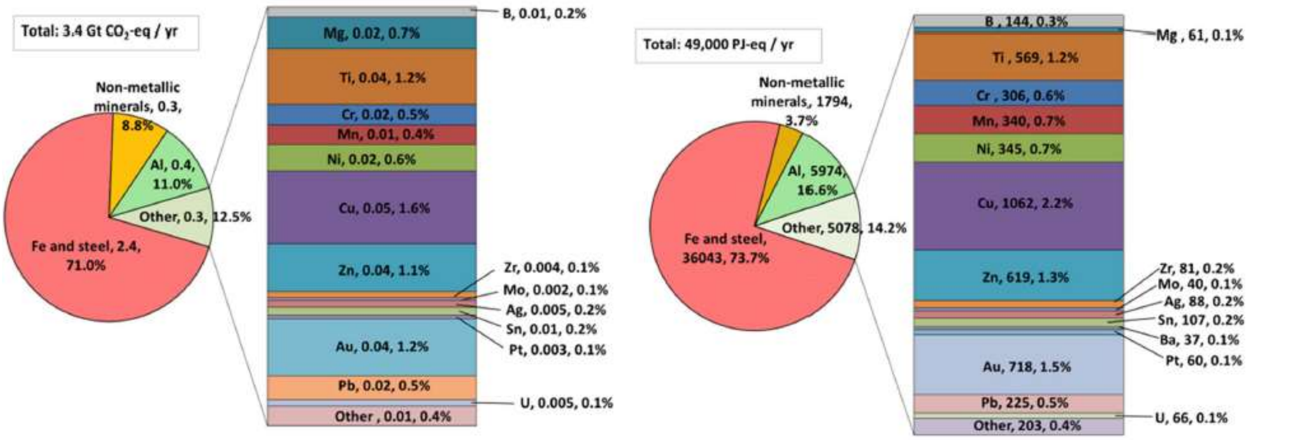
- An environmental assessment of raw materials has to take into account other environmental factors besides toxicological risks. This method of assessment can therefore only form part of a comprehensive assessment.

- Generally speaking, there is plenty of data relating to metals, but this is not sufficient for a toxicological assessment of mineral deposits (which usually take the form of extremely complex composite minerals). This is because the toxicological impact of mining and processing is often due to the toxicological effects not only of the main products and by-products, but also of the auxiliary substances used in processing and the waste materials which are often left on site (Priester, Dolega 2015).

3.2 LCA-based methods of assessment

In the course of the creation of environmental assessment databases, such as ProBas and EcoInvent, data has been collected and processed on the cumulative energy demand (CED) and global warming potential (GWP) of many raw materials and on other indicators, such as eutrophication, acidification potential, and water and land consumption. This data has been used in various investigative studies which involve a comparative environmental assessment of raw materials. Nuss and Eckelman (2014) used the data on primary energy consumption and global warming potential of particular raw materials as the basis on which to compare a variety of mineral resources. The results show that the global production of iron and steel is strongly dominant in both these categories and accounts for 71% of total annual greenhouse gas emissions and almost 74% of total annual primary energy consumption associated with all the raw materials included in the study (see Figure 1).

Figure 1 A comparison of abiotic raw materials on the basis of global warming potential and primary energy consumption involved in production



Quelle: Nuss, Eckelman (2014)

Comparative studies such as these are valuable in so far as they throw light on particular environmental aspects of the raw materials economy. Nevertheless, various problems are associated with the exclusive use of existing LCA data. This means that the assessments cannot be regarded as reliable when considering the totality of environmental impacts:

- The values contained in the data are often derived from a relatively small sample of mining, processing, and smelting sites. There is therefore a risk of significant inaccuracy when extrapolating data to the global (production) level.
- The indicators for greenhouse gas (GHG) emissions and cumulative energy demand (CED) shown in Figure 1 are relatively well underpinned by primary data in the case of many raw materials, although the data is rarely representative, as outlined above. But the data available for other factors, such as water and land consumption and acidification potential, is altogether very scanty. So, for example, the calculation of acidification potential may be based on actual figures for SO_2emissions. But in some cases these figures only include emissions from production of the electricity used. Other potential sources of acidification, such as auto-

oxidation of residues from processing, are not normally included in the recorded data, in spite of the fact that they have been shown to have a major environmental impact where some raw materials are concerned.

- There is a comparable lack of data relating to emissions of other pollutants such as heavy metals and arsenic: On the one hand, emissions from power plants for electricity generation are usually included in the databases. But there is a lack of quantitative information on pollution problems from mining waste and from the use of auxiliary chemicals in processing. The last point especially should not be neglected, given that the quantity of waste is often very large and that accidents continue to occur frequently (often as a result of dam failures).
- Various impacts, especially those associated with direct intervention in the natural environment, are extremely difficult to quantify in any attempt to assess the overall environmental impact. It is possible to use data on water and land use to make a rough estimation (of overall environmental impact). But relevant data is lacking in terms of both quantity and quality. And where such data does exist, the indicators are usually nothing more than an inventory and do not include any information about the ecological value or significance of the land or water catchment areas which are affected.

3.3 Use of environmental criteria in estimating supply risks

Since 2018, in the course of the debate on risks to the supply of raw materials, a growing amount of work has been done on developing methods for the comparative evaluation of abiotic raw materials. The main aim of many of these newly-developed approaches is to assess: the risks to the supply of individual raw materials; and the vulnerability (to disruptions of supply) of a system which uses them (e.g. a national economy, an industrial sector, or a company). The ultimate aim is to be able to assess the so-called "criticality" of individual raw materials. Many authors emphasise that the environmental and social impacts of mining projects have a significant influence on the availability of raw materials and may therefore constitute a supply risk.

In its study of raw materials which are critical for the US economy (National Research Council of the National Academies 2008), the National Research Council of the National Academies of the USA has included environmental and social availability as one of five factors influencing the availability of primary raw materials. In the description of the method of assessment for this particular factor, attention is drawn especially to situations such as those during the gold rushes in California and Alaska and the mining of oil sands in Canada in recent years. The sudden rapid expansion of mining meant that spatial planning and the development of infrastructure were no longer able to keep pace with mining activities. According to the authors of the study, such situations can impose excessive burdens on local inhabitants and lead to conflict over land use and environmental impact. The study also points to the fact that growing urbanisation of mining locations can lead to land use conflicts between mining and other activities. According to the authors, where the availability of minerals is concerned, the development of settlements is especially relevant, because it often hinders the exploitation of deposits. However, the observations on this subject did not find any practical application in terms of relevant indicators to be used in the assessment of criticality. This was no doubt largely due to a lack of suitable data relating to specific raw materials.

This analysis of the problem of the availability of raw materials is also supported by Prior et al. (2012). Using Australia as an example, they show that conflicts - both real and anticipated - over land use and the environmental impacts of mining are already having a negative impact on the availability of raw materials. Increased awareness of environmental problems also results in higher extraction costs, because mining activities in Australia are increasingly subject to state (environmental) regulations and voluntary commitments, so that external environmental costs are internalised at least to some extent (Prior et al. 2012).

The working group around Graedel (Graedel et al. 2012; Graedel et al. 2015) has been prompted by these arguments to acknowledge that environmental impact is a key factor influencing the availability of raw materials and to record environmental impact using practical indicators. According to this way of thinking, environmental implications (EI) are a dimension which is just as important as supply risk and vulnerability and which therefore represents a third dimension in the discussion about critical raw materials. For practical purposes, the authors suggest using LCI data - from the EcoInvent database, for example - to create a picture of the two categories of harm: harm to human health and harm to ecosystem quality (i.e. the two categories of impact: human toxicity and ecological toxicity)[4].

The European Commission also recognises a high degree of environmental risk as part of a high supply risk[5]. And the Ad hoc Working Group on Defining Critical Raw Materials included environmental factors - in the form of the Environmental Performance Index (EPI) - in the calculation of the European supply risk and hence the criticality of raw materials for the EU (EU Commission 2010). This was not included in the current revision/update of the EU study (EU Commission 2014), however, because the EPI was seen not to be entirely appropriate[6].

This means that the current methodologies for estimating the criticality of raw materials - with the exception of the assessment method of Graedel et al. - address environmental criteria only very indirectly, if at all. This last point is significant when, for example, potentially profitable deposits cannot be counted as reserves in a country's statistics, because the designation of protected areas has made it impossible for the deposits to be legally exploited.

4 When adopting this approach, it is necessary to take into account the fact that the problems described in section 3.2, as regards reliability and the availability of data, remain. A further limitation should be seen in the fact that toxic impacts are only taken into account if they fit into one of the systems of classification which are part of current scientific discourse.

5 EU Commission (2010): "To qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance."

6 "The Ad hoc Working Group on Defining Critical Raw Materials raised the concern that not all parameters of the complex Environmental Performance Index (EPI), which was initially part of the "supply risk" assessment component, are relevant for the assessment of the criticality of raw materials. In certain cases the EPI did not reflect the reality in the mining sector of certain countries resulting in an artificial move in the supply risk calculation." (p. 22, EU Commission, 2014).

4 A method for raw materials related assessment of environmental hazard potentials

4.1 Framework of assessment

In order to be able to carry out an environmental assessment of abiotic raw materials, the frame of reference of the assessment needs to be defined in advance (scoping). In this study, the following reference points have been established:

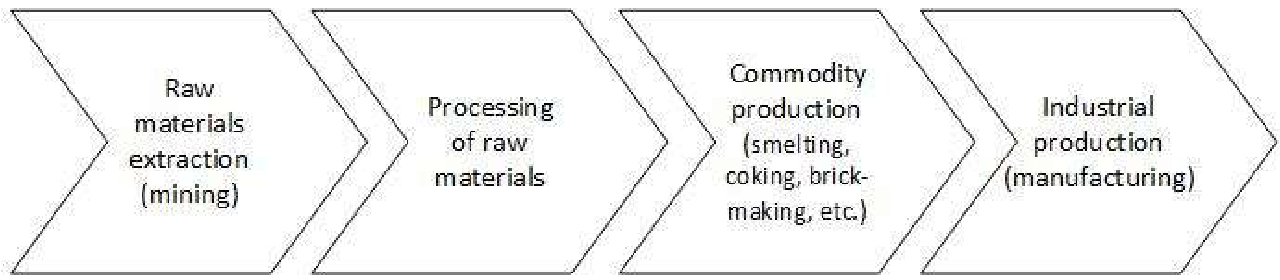
1. The method is intended to make it possible to assess abiotic raw materials obtained from mining.
2. The assessment is carried out with reference to standard raw materials as shown in Table 1. This approach is intended to ensure that the method can be added on to the criticality assessments which have already been developed (see section 3.3).
3. The assessment therefore focuses on the first stages in the value chain: mineral extraction (mining) and processing. The production (smelting, coking, brick making, etc.) of raw materials is included to a limited extent (see Figure 2 and section 4.3). It is consciously acknowledged that different system limits have been chosen for different individual indicators. This is possible because, unlike in the case of life cycle assessments, no quantitative comparisons are being made. Where comparative life cycle assessments are concerned, the systems being compared need to serve the same purpose. The limits of the system can be chosen in order to ensure this. In the largely qualitative assessment of environmental hazard potentials used here, the targeted, transparent extension of the system limits in the case of two indicators does not lead to an unwanted distortion of the results.
4. The EHP ratings relate to total global production of the raw materials concerned. This has the advantage that the environmental hazard potentials are included in the assessment on the basis of their global magnitude. But another consequence of using this approach is that the assessment does not allow for an environmental comparison of defined quantities of raw materials (e.g. 1 t of raw material A in comparison with 1 t of raw material B).

Table 1 Abiotic raw materials in the EU study of critical raw materials (EU Commission 2014)

Name of raw material (German)	Name of raw material (English)	Chemical formula	Additional description
Aluminium	Aluminium	Al	
Antimon	Antimony	Sb	
Baryt	Barytes	$Ba[SO_4]$	Barium sulphate, also referred to as barite
Bauxit	Bauxite	-	Aluminium ore consisting of various aluminium minerals and iron oxides
Bentonit	Bentonite	-	Silicate clay with a high proportion of the clay mineral montmorillonite
Beryllium	Beryllium	Be	
Borate	Borates	-	Various minerals containing boron
Chrom	Chromium	Cr	
Diatomit	Diatomite		Powdery substance consisting of diatoms. Also referred to as diatomaceous earth or kieselgur/kieselguhr
Eisenerz	Iron ore	Iron oxide & carbonates	
Feldspat	Feldspar	-	Various silicate minerals
Flussspat	Fluorspar	CaF_2	Mineral form of calcium fluoride, also referred to as fluorite
Gallium	Gallium	Ga	
Germanium	Germanium	Ge	
Gips	Gypsum	$Ca[SO_4]\ 2H_2O$	Due to a significant proportion of gypsum production being from flue gas desulphurisation, primary gypsum deposits are referred to as "natural gypsum".
Gold	Gold	Au	
Graphit	Natural graphite	C	Elemental Carbon
Hafnium	Hafnium	Hf	
Indium	Indium	In	
Kaliumcarbonat	Potash	K_2CO_3	
Kalkstein	Limestone	$CaCO_3$	
Kaolin & Kaolinit	Clay (kaolin and kaolinite clay)	$Al_4[(OH)_8\|Si_4O_{10}]$	Two-layer clay minerals
Kobalt	Cobalt (Cobaltum)	Co	
Kokskohle	Coking coal	-	Produced by pyrolysis (coking) and desulphurisation of coal
Kupfer	Copper	Cu	
Leichte Seltene Erden	Light rare earth elements (LREE)	La, Ce, Pr, Nd, Sm	In the EU study on critical metals, rare earth elements are divided into 3 groups: light rare earth elements, heavy rare earth elements, and scandium
Lithium	Lithium	Li	
Magnesit	Magnesite	$Mg\ [CO]_3$	

Name of raw material (German)	Name of raw material (English)	Chemical formula	Additional description
Magnesium	Magnesium	Mg	
Mangan	Manganese	Mn	
Molybdän	Molybdenum	Mo	
Nickel	Nickel	Ni	
Niob	Niobium	Nb	
Perlit	Perlite	-	amorphous volcanic glass
Phosphatgestein	Phosphate rock		Also known as phosphorite; (magmatic) apatite ores and phosphorite ores (sedimentary deposits)
Platingruppenmetalle (PGM)	Platinum group metals	Pt, Pd, Ru, Rh, Os, Ir	
Rhenium	Rhenium	Re	
Scandium	Scandium	Sc	Classified as one of the rare earth elements
Schwere Seltene Erden	Heavy rare earth elements (HREE)	Y, Pm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	In the EU study on critical metals, rare earth elements are divided into 3 groups: light rare earth elements, heavy rare earth elements, and scandium
Selen	Selenium	Se	
Silber	Silver	Ag	
Silikatsand	Silica sand	SiO_2	Also known as quartz sand
Silizium	Silicon metal	Si	Metallic raw silicon (approx. 99% pure silicon) obtained from quartz (SiO_2)
Talk	Talc	$Mg_3Si_4O_{10}(OH)_2$	
Tantal	Tantalum	Ta	
Tellur	Tellurium	Te	
Titan	Titanium	Ti	
Vanadium	Vanadium	V	
Wolfram	Tungsten	W	
Zink	Zinc (Zincum)	Zn	
Zinn	Tin	Sn	

Figure 2 Generic value chain of raw materials obtained through mining



Source: Own representation

4.2 Paradigm Shift: from the calculation of environmental impact to the assessment of environmental hazard potentials

As shown in chapter 3, the wide variety of environmental impacts from the extraction of abiotic raw materials can only be quantified very roughly at present. This means that the current usual approaches to a comparative environmental assessment are unable to access sufficient data (measurements and averages) on the various emissions, levels of consumption, and resulting environmental impacts of specific raw materials. Comparatively robust approaches are dependent on a small number of indicators (primary energy consumption and global warming potential, in particular) which means that there are significant environmental impacts which they inevitably fail to take into account. Depending on the question being asked, the results are either not very or not at all reliable.

There will continue to be a lack of data, as described in section 3.2, for the foreseeable future. So during the ÖkoRess project an approach to assessment using environmental hazard potentials has been developed on the basis of available knowledge and the evaluation of 40 case studies. This makes site-related assessment of mining projects possible. In order to provide useful input for criticality models, the site-related system of assessment has been converted (as far as possible) into a raw material related assessment.

The approach is characterised by the idea that significant environmental impacts arising from raw materials extraction are directly related to:

- geological conditions (e.g. geochemical composition of deposits);
- technical requirements of extraction and processing (e.g. open-cast or underground mining, form of processing);
- and the environmental characteristics of mining sites (e.g. availability of water, risk of accidents induced by natural events, fragility of the affected ecosystem).

In the case of geological conditions (which will be referred to as the “geology level”) in particular, the deposits of any particular raw material usually occur in a similar geological context. This can be attributed largely to the fact that deposits of any particular raw material have often been formed under similar conditions and through similar processes of enrichment. There are some raw materials (e.g. gold) which are found in very different types of deposits which have been formed in very different ways. Nevertheless, this broad spectrum of deposit types can be narrowed down into a few main groups. Alternatively, in some cases, deposits have already been classified in the course of research (see Cissarz 1965, for example). Looked at from this point of view, it is possible, among other things, to deduce whether a particular type of raw material deposit has a high or low concentration of heavy metals and sulphides. If the typical concentrations are relatively high, the corresponding environmental hazard potential is assessed as high accordingly.

Technical requirements (which will be referred to as the “technology level”) can be assessed in a similar manner. Together with the prevailing economic conditions (pressure to reduce costs) and the global spread of mining machinery and processes, this also means that similar deposits around the world are exploited using similar technical processes. It is therefore possible to make valid general statements regarding the characteristics of particular raw materials. This is relevant where environmental assessment is concerned, because some of these characteristics also serve as a source of information about potential environmental problems, as illustrated by the following example: If large quantities of chemicals are used in the processing of a raw material, there is generally a significant risk that they will be released into the environment. It can be assumed that the raw material concerned occurs in numerous deposits around the world and is exploited in a large number of mines, in which case one must not ignore the likelihood that such chemicals will not always be handled properly. This means that a particular raw material can be assigned a low, medium, or high level of environmental hazard potential according to its characteristics at the "technology level".

The third assessment level is concerned with the characteristics of the particular site. (This will be referred to as the "natural environment level".) Here, the assessment is based on the assumption that certain environmental impacts are especially dependent on the local conditions. So, for example, the risk of accidents induced by natural events is especially high in regions which are affected by flooding, earthquakes, storms, and/or landslides. The raw material related method of assessment, which is the subject of this report, is based on the assumption that the environmental hazard potential of a raw material is especially high, when a large proportion of global production takes place within regions which are affected by such natural events.

In relation to all three of the levels described above, it should be noted that this method of assessment does not take into account practical risk management or countermeasures to prevent environmental impacts. This should not be taken to imply that such measures are ineffective. On the contrary. The authors acknowledge that in many mining projects negative environmental impacts can be reduced effectively using appropriate practical measures, even where there is a high environmental hazard potential. And in many areas the risks of environmental impacts induced by natural events can similarly be reduced, if good care is taken. However, looking at things from a global perspective, one has to assume that in many projects and regions measures to reduce environmental impact and accident risks are implemented inadequately, if at all. There are various reasons for this, such as cost pressures and governance issues.

The method aims, using a combination of different indicators, to assess the scale and likelihood of environmental impacts from the extraction and processing of a raw material. The method uses a rough assessment grid, in which a low, medium, or high level of environmental hazard potential (EHP)can be entered for each raw material and for each indicator.

4.3 Additional indicators for the raw material value chain

As explained at the beginning of chapter 4, the aim is to assess standard commodities which are the product of the first three stages of the value chain as illustrated in Figure 2. The procedure outlined in section 4.2 was largely derived from the site-related method of assessment, although this is based solely on consideration of the first two stages of the value chain and therefore excludes the stage of raw material production (smelting, coking, brick making, etc.). These production processes are usually carried out at some distance from extraction sites (mines). And there is usually a large number of complex steps in such production processes. It is therefore not normally possible to account for the environmental effects of this stage of the value chain in the site-related assessment process. A further level has therefore been added to the raw material related assessment grid, so that it gives an indication of the order of magnitude of the environmental hazard potential of the whole value chain from mineral extraction (mining) to raw material production, e.g. smelting (See Figure 2). Use is made in particular of existing LCI data on primary energy consumption, i.e. cumulative energy demand (CED). For many raw materials, this indicator can be recorded alongside other existing environmental assessment data. However, this also means that other environmental impacts from the raw material production stage of the value chain (e.g. smelting) can only be included in the assessment indirectly or not at all. While LCI data exist for other environmental impacts from raw material production, e.g. emission of pollutants, these are based in many cases on measurements at individual sites which are not representative. Use of this data would also contradict the approach chosen here, which is to show the environmental hazard potential of the whole value chain (mineral extraction, processing, raw material production), because the available data does not meet the necessary requirements due to the inadequacies described in section 3.2.

However, an indirect assessment is possible using specific raw material related indicators for geogenic heavy metals, radioactive substances, and sulphide content (see Table 2). This is possible because the geochemical composition of minerals also serves as an indicator of potential emissions of pollutants such as heavy metals, radioactive substances, and SO_x during raw material extraction and waste management[7].

The "cumulative raw materials demand" indicator, which also appears under the heading "value chain" in Table 2, serves as an indicator of the scale of potentials, effects, and impacts at the global level. Among other things, it also replaces the site-specific "size of deposit" indicator in the site-related assessment grid.

4.4 The role of environmental governance

The authors also recommend that environmental governance indicators be taken into account in the assessment of environmental hazard potential, in order to present a rough picture of the capacities of affected countries for dealing with potential environmental hazards. Their practical suggestion is that the World Bank's country governance indicators be used in assessments. This recommendation is based on the following thinking:

As shown in section 4.2, the method of assessment presented here is based on an estimation of environmental hazard potential. However, for reasons of impracticality, this does not take account of precautionary measures which could potentially be taken by mining companies. Nevertheless, in order to estimate the extent to which effective environmental standards may be applied, the general assumption is made that effective environmental protection measures will be implemented especially in countries with good governance. It is of course possible for mining companies to implement high standards in regions with poor governance as well (on a voluntary basis, for example). But, as a rule, there are generally more opportunities to reduce costs by implementing standards only partially or not at all. This is made easier by the fact that in some jurisdictions either no standards or only poor standards are enforced, or they can be evaded with little cost or risk to the business.

A detailed description of the methodology is presented in section 5.4.1. This represents the interim results as regards socio-political factors which may increase or reduce risk. In-depth observation of governance issues and further development of relevant methods of assessment will be addressed as part of the ÖkoRess II project (FKZ 3715 32 310 0). The results will be published subsequently.

4.5 The raw material related assessment grid

The method outlined in section 4.2 is summarised in the assessment grid shown in Table 2. The process for the assessment of the individual indicators is set out in chapter 5.

7 The "ÖkoRess II" project (FKZ 3715 32 310 0) will include quantitative descriptions of other environmental impacts from raw materials extraction and similar information in profiles of individual raw materials.

Table 2 Grid for the assessment of raw material related environmental hazard potentials (EHP)

	Target	Indicator	Assessment		
			Low EHP	Medium EHP	High EHP
Geology	Reduction of pollution risks	1. Preconditions for Acid Mine Drainage (AMD)	Geochemical conditions for AMD are not present	Geochemical conditions for AMD are partially present	Geochemical conditions for AMD are present
		2. Associated heavy metals	Raw material deposits do not normally exhibit heightened concentrations of heavy metals	Raw material deposits normally exhibit slightly higher concentrations of heavy metals	Raw material deposits normally exhibit high concentrations of heavy metals
		3. Associated radioactive substances	Raw material deposits normally exhibit low concentrations of uranium and/or thorium	Raw material deposits normally exhibit slightly higher concentrations of uranium and/or thorium	Raw material deposits normally exhibit high concentrations of uranium and/or thorium
Technology	Limitation of destruction of the natural environment	4. Method of extraction	Mineral is usually extracted by underground mining	Mineral is usually extracted by surface mining of solid rock	Mineral is usually extracted by open-cast mining of loose rock or alluvial deposits, or by dredging rivers
	Reduction of pollution risks	5. Use of auxiliary chemicals	Standard methods of extraction do not involve the use of auxiliary chemicals	Standard methods of extraction involve the use of auxiliary chemicals	Standard methods of extraction involve the use of toxic auxiliary chemicals
Natural Environment	Prevention of accidents induced by natural events	6. Risk of accident due to flooding, earthquakes, storms, or landslides	Threshold values for medium and high EHP are not exceeded.	>X% active mines in areas with medium risk of naturally induced accidents	>Y% active mines in areas with high risk of naturally induced accidents
	Prevention of water conflicts	7. Water Stress Index (WSI) and arid regions	Threshold values for medium and high EHP are not exceeded.	>X% active mines in areas with moderate water stress	>Y% active mines in areas with high water stress or in arid regions
	Protection of valuable ecosystems	8. Designated protected areas and AZE sites	Low environmental hazard potential	>X% active mines in protected areas or AZE sites	>Y% active mines in highly protected areas
Governance Environment	Implementation of standards	9. Environmental governance in the most important producing countries	None of the three leading producing countries has a WGI rating of less than 50% for the Voice & Accountability and Control of Corruption indicators	None of the three leading producing countries has a WGI rating of less than 25% for the Voice & Accountability and Control of Corruption indicators	At least one of the three leading producing countries has a WGI rating of less than 25% for the Voice & Accountability and/or the Control of Corruption indicators
Value Chain	Reduction of global EHP	10. Cumulative raw materials demand of global production ($CRMD_{global}$)	$CRMD_{global}$ < 16.5 million tonnes per year	$CRMD_{global}$ 16.5 - 200 million tonnes per year	$CRMD_{global}$ > 200 million tonnes per year
	to reduce the global EHP	11. Cumulative energy demand of global production (CED_{global})	CED_{global} < 10,000 TJ per year	CED_{global} 10,000 - 100,000 TJ per year	CED_{global} > 100,000 TJ per year

5 Measurement Guidelines

The following guidelines for measurement serve as an explanation and an aid to application of the assessment grid in Table 2. Most of the core elements of the measurement guidelines were developed as part of the site-related method of assessment and are also documented in ÖkoRess I, Report No. 2[8]. Adjustments were made in so far as the measurement guidelines for the raw material related assessment require a broader general approach which addresses the global situation as regards the mining of each particular raw material. It was necessary to make a number of more far-reaching adjustments, which can be summarised as follows:

- The “deposit size” indicator used in the site-related approach is no longer applicable at the global level. This indicator has therefore been omitted. However, the goal of limiting destruction of the natural environment is still covered by indicator no. 4 , “method of extraction”. Two other indicators also have an influence: No. 10. “cumulative raw materials demand ($CRMD_{global}$)”, which shows the scale of environmental impacts measured by all the indicators; and No. 8. “designated protected areas and AZE sites”, which pays special attention to areas which are especially worth protecting and in which intervention could have especially serious consequences.
- The “deposit composition” indicator used in the site-related approach is no longer applicable at the global level and has therefore been omitted. However, information about typical levels of concentration in deposits and the inputs required for the extraction of individual raw materials is included in the new indicators no. 10 (“global cumulative raw materials demand”, $CRMD_{global}$) and no. 11 (“global cumulative energy demand”, CED_{global}).
- Two of the indicators used in the site-related assessment, relating to waste management and site rehabilitation, are not included, because they are not reliable enough to be applicable at the global level.
- In order to nevertheless take account of factors relating to management and the enforcement of environmental standards, the site-related indicator for governance was adjusted: The new indicator no. 9, which rates environmental governance in the leading producing countries, is intended to give an indication of the degree of risk of standards being disregarded in the main producing countries.
- In principle it is possible to transfer the indicators for risks associated with the immediate environment of mining sites (No. 6 “risk of accidents induced by natural events”; No. 7 “water stress and arid regions”; No. 8 “designated protected areas and AZE sites”) to a raw materials related assessment using geocoded data. The available data has a number of limitations, however. And, as with all the other indicators, it is necessary to set boundaries for the assessment of the ratings (low, medium, high EHP).
- In order to take account, in the assessment, of the magnitude of intervention in the environment by global mining activities, a fourth level has been added to the assessment of value chains. This comprises two indicators for the consumption of energy and raw materials, each of which will be described in detail in the relevant sections of this chapter.

5.1 Geology Level

The geochemical composition of minerals is a significant factor determining pollution risks from mining. As regards ores in particular, pollution risks can be classified basically as follows:

8 ‘Evaluation of the environmental hazard potentials involved in the extraction of abiotic primary raw materials – A methodology for a site-related approach’ - ÖkoRess I, Report No. 2

- Preconditions for Acid Mine Drainage (AMD)
- Association with heavy metals and/or arsenic
- Association with radioactive substances

In addition to these preconditions, pollution risks may arise from auxiliary chemicals used in the processing of ores. These will be dealt with in section 5.2.2.

Goal-oriented management measures can significantly reduce emissions of pollutants into the environment. But it is normally only possible to assess the effectiveness of particular combinations of measures by means of costly on-site inspections. This means that this factor has to be omitted from the initial assessment of environmental hazard potentials which is being attempted here.

5.1.1 Indicator 1: Preconditions for Acid Mine Drainage (AMD)

Assessment

Low EHP:

Geochemical conditions for AMD are not present (lithophile raw materials)

Medium EHP:

Geochemical conditions for AMD are present to some extent (raw materials are siderophile in pure form or occur as oxides)

High EHP:

Geochemical conditions for AMD are present (raw materials present as sulphides or in sulphide ore deposits)

Acid mine drainage is considered to be one of the most serious environmental problems in mining. It denotes the formation of acid drainage, outflows of which usually have serious environmental impacts on groundwater and surface water in the catchment area concerned. The formation of acid drainage is dependent on various factors such as particle size and the range of particle sizes in processing residues or spoil heaps, the abundance of moisture, and ambient temperatures (Akcil, Koldas 2006). One major factor, however, is the chemical composition of spoil heaps and processing residues. AMD normally requires the presence of sulphide minerals. If these are exposed to moisture and oxygen (in the air), a series of chemical reactions leads to oxidation and hydrolysis and hence to the formation of acid drainage. This acid drainage may then leach heavy metals out of the rock and aggravate the environmental problem even further (Udayabhanu, Prasad 2010). The magnitude of the environmental problem arising from AMD is very much dependent on the particular conditions in each mining area and on the implementation of any counter-measures. But typical geochemical combinations provide a useful indication of the order of magnitude of the risks involved.

The tendency towards auto-oxidation of ores and mining waste can be deduced from the preferred conditions for the formation of the ores (of the metals or valuable elements which are being mined and of any associated minerals). The geochemical conditions of formation vary according to the type of element. The elements are classed as siderophile (iron-loving), lithophile (silicate-loving), or chalcophile (sulphur-loving) in the Goldschmidt classification (see Figure 3[9]). This classification, which makes an initial analysis possible, is based on the typical process of enrichment of elements in the geosphere: Whereas siderophile elements were mostly enriched in the iron core of the Earth, lithophile elements are more likely to occur in higher concentrations in the Earth’s crust. The latter are

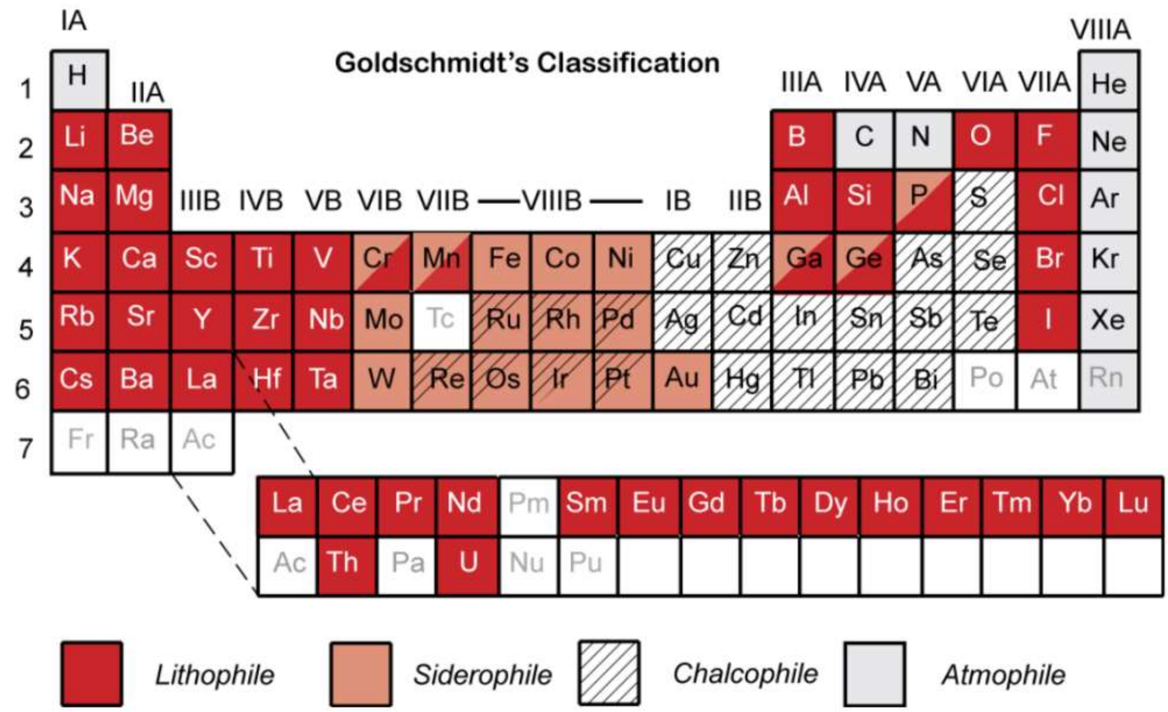
9The atmophile (gas-loving) elements which are also included in this classification are not relevant in this context.

characterised by high energy bonding of oxides, which makes it unlikely that the element occurs naturally in pure form or is easily dissociated (White 2013, Geochemistry). Chalcophile elements, in their turn, occur predominantly as sulphides. This classification makes it possible to deduce for each particular raw material whether the conditions for acid mine drainage are present:

- Lithophile elements are usually extracted from oxide deposits.
- Chalcophile elements are usually extracted from sulphide deposits.
- Siderophile elements often occur as sulphides, but are also extracted from oxide deposits. This applies above all to deposits which have been exposed to atmospheric weathering over a long period of time.

Especially when conducting an economic and geological analysis, it is essential - for the purposes of understanding and assessment - to consider the paragenetic conditions of the ores in commercially viable deposits. In the case of siderophile elements, this can often lead to inclusion in the group of lithophile elements. On this subject, see Figure 3 and the text which follows.

Figure 3 Representation of the Goldschmidt classification of the elements (White 2013)

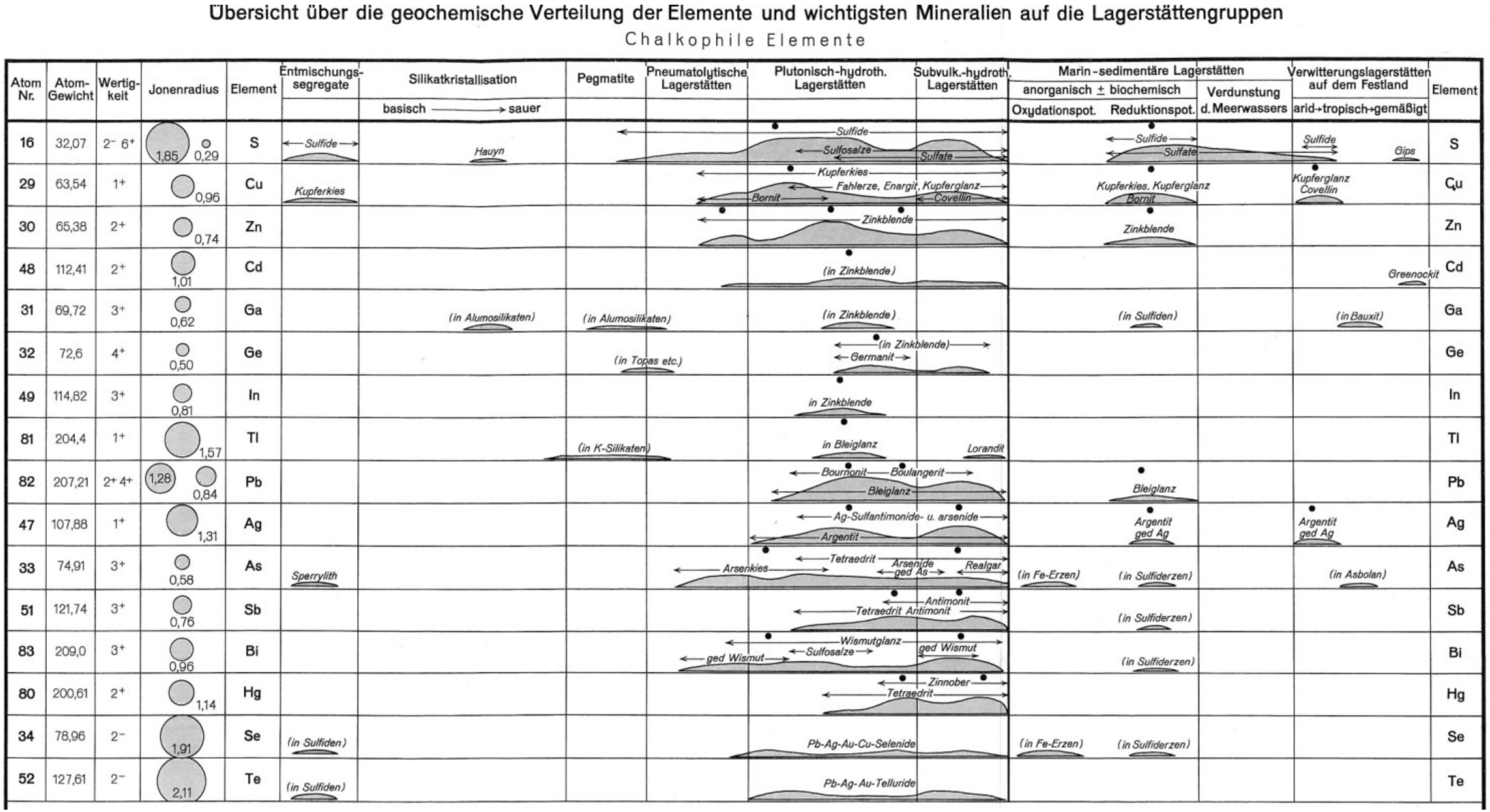


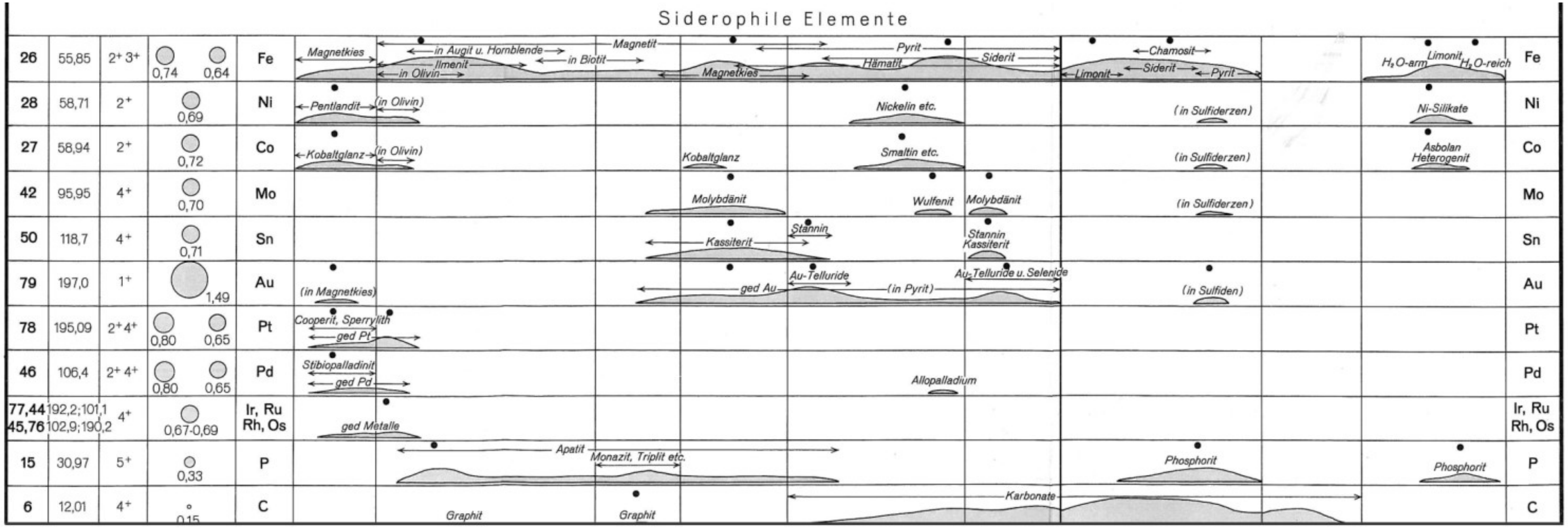
Where the geology of deposits is concerned, these characteristics of specific elements can be transferred to ores and mineral parageneses. This is illustrated for the various geological conditions of formation according to Cissarz (1965) in Figure 4.

In Figure 4 a black dot denotes an economically important ore. For each of the ores in this figure, minerals which occur in associated assemblages appear in the same column [10]. These minerals may be equally responsible for AMD, especially where sulphide minerals are concerned.

10 For example: Nickel from pentlandite ore in segregation deposits occurs paragenetically together with chalcopyrite (also in the segregation minerals column), sperrylith, selenium and tellurium sulphides, pyrrhotite, cobaltite, gold, and PGM.

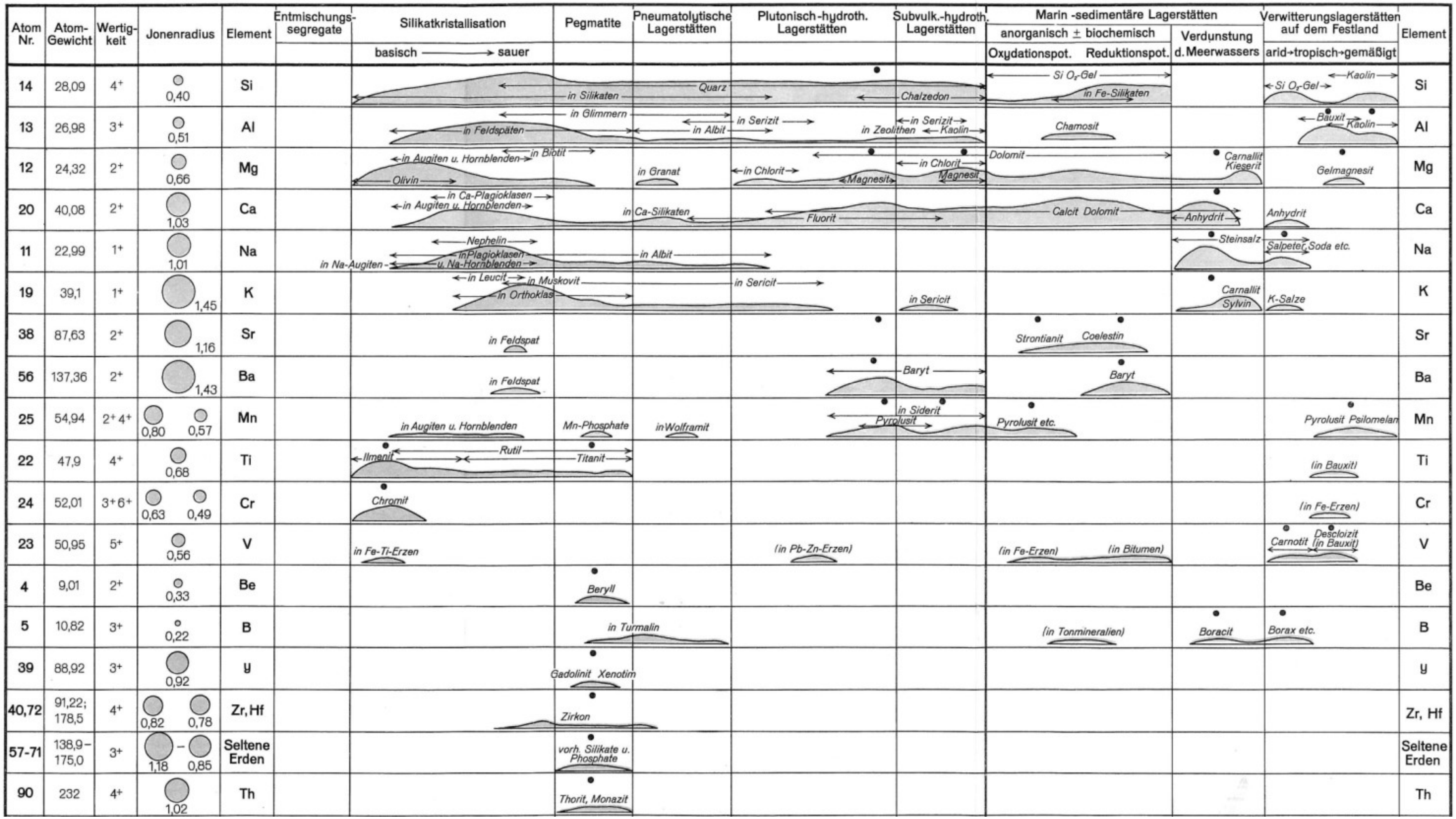
Figure 4 Geochemical distribution of the elements and most important minerals (Cissarz 1965)

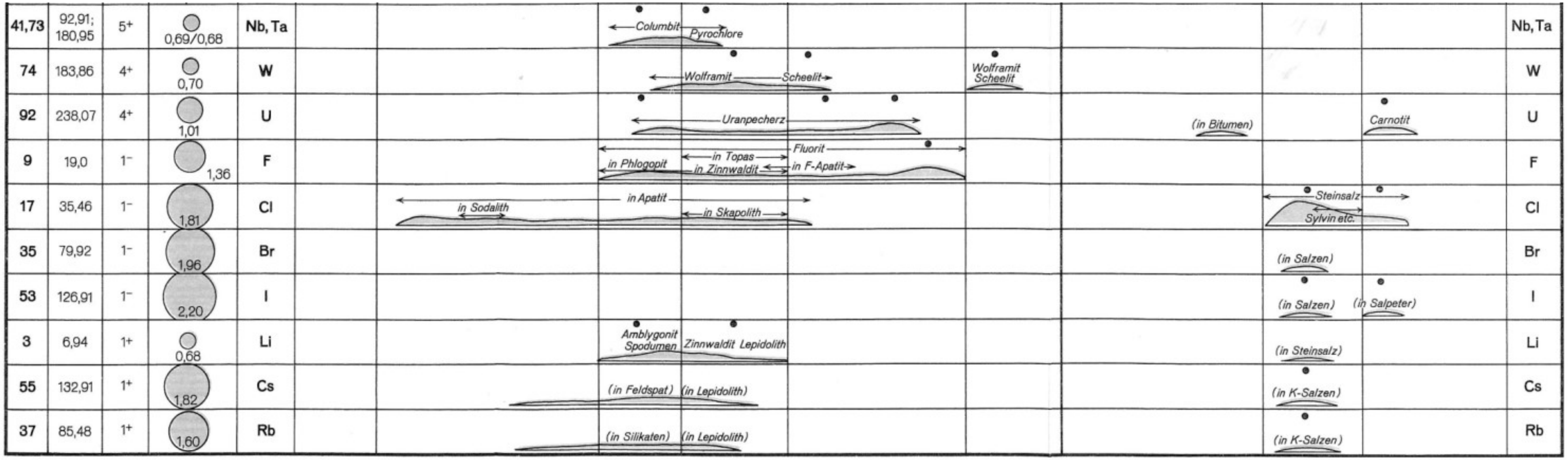



Siderophile Elemente
26 55,85 2+ 3+ 0,74 0,64 Fe
Magnetkies
in Augit u. Hornblende
Ilmenit
in Olivin
in Biotit
Magnetit
Magnetkies
Pyrit
Hämatit
Siderit
Chamosit
Limonit
Siderit
Pyrit
H_2O-arm Limonit H_2O-reich
28 58,71 2+ 0,69 Ni
Pentlandit
(in Olivin)
Nickelin etc.
(in Sulfiderzen)
Ni-Silikate
27 58,94 2+ 0,72 Co
Kobaltglanz
(in Olivin)
Kobaltglanz
Smaltin etc.
(in Sulfiderzen)
Asbolan
Heterogenit
42 95,95 4+ 0,70 Mo
Molybdänit
Wulfenit
Molybdänit
(in Sulfiderzen)
50 118,7 4+ 0,71 Sn
Kassiterit
Stannin
Stannin
Kassiterit
79 197,0 1+ 1,49 Au
(in Magnetkies)
ged Au
Au-Telluride
(in Pyrit)
Au-Telluride u. Selenide
(in Sulfiden)
78 195,09 2+ 4+ 0,80 0,65 Pt
Cooperit, Sperrylith
ged Pt
46 106,4 2+ 4+ 0,80 0,65 Pd
Stibiopalladinit
ged Pd
Allopalladium
77,44 45,76 192,2;101,1 102,9;190,2 4+ 0,67-0,69 Ir, Ru Rh, Os
ged Metalle
15 30,97 5+ 0,33 P
Apatit
Monazit, Triplit etc.
Phosphorit
Phosphorit
6 12,01 4+ 0,15 C
Graphit
Graphit
Karbonate

Übersicht über die geochemische Verteilung der Elemente und wichtigsten Mineralien auf die Lagerstättengruppen

Lithophile Elemente





The following guidelines for assessment can be derived from this:

- The lithophile elements consistently exhibit a low EHP as regards AMD. This applies to the following minerals: bauxite/aluminium, magnesite/magnesium, silicate sand/silicon, chalk/calcium, potassium carbonate/potassium, manganese, titanium, chromium, vanadium, barite, beryllium, borate/ boron, zircon, hafnium, rare earths, niobium, tantalum, tungsten[11], lithium.
- The chalcophile elements consistently exhibit a high EHP as regards AMD. This applies to the following minerals: sulphur, copper, zinc, cadmium, germanium[12], indium, tellurium, lead, silver, antimony, bismuth.
- Gallium is an exception, which may be classified as a siderophile, chalcophile, or lithophile element, depending on its source. But it does not occur in commercially viable concentrations in any of the corresponding deposits. Gallium is usually obtained from bauxite as a by-product, so the EHP of gallium is analogous to that of aluminium/bauxite (lithophile) and therefore rated as low.
- The situation is less clear where the siderophile elements are concerned: iron, nickel, cobalt, molybdenum, tin, gold, the platinum group metals, rhenium, and phosphorus. These raw materials usually occur in oxide minerals, whereby the particular aggregate (including associated minerals) is often likely to contain sulphides. In these cases, a medium rating is recommended, although in the case of site-related assessments it is important to note the following exceptions:

11 Tungsten is listed as a siderophile element in Figure 3, but it can be seen from Figure 4 that commercially viable deposits are invariably lithophile.

12 Germanium is usually obtained as a by-product from complex copper and zinc sulphide ores, so it is classified as chalcophile (see Figure 4).

1. Soap deposits - which may be relevant especially in relation to the extraction of gold, PGM (platinum group metals), and tin - are usually oxidic and exhibit a low risk of AMD.
2. Molybdenum is usually a by-product of copper extraction. In this case, it must be assumed that there is a high risk of AMD.
3. Gold is sometimes obtained from copper deposits as well. These deposits also exhibit a high risk of AMD.
4. Nickel and cobalt ores usually occur in the form of iron-nickel-cobalt sulphide minerals, e.g. nickel pyrrhotite. So nickel and cobalt deposits usually have to be rated as high risk for AMD.

5.1.2 Indicator 2: Assemblages containing heavy metals

Assessment

Low EHP:

Raw material deposits do not normally exhibit heightened concentrations of heavy metals.

Medium EHP:

Raw material deposits normally exhibit slightly higher concentrations of heavy metals.

High EHP:

Raw material deposits normally exhibit high concentrations of heavy metals.

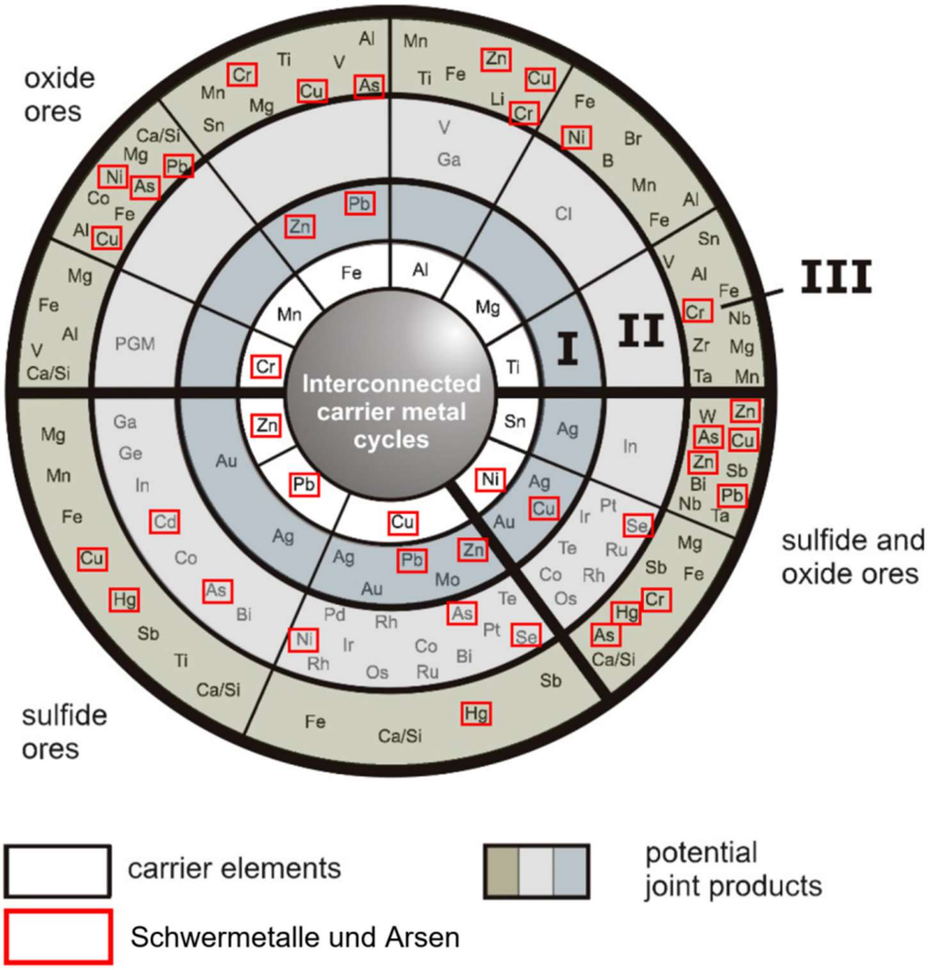
Heavy metals are mostly a problem in the mining and processing of metal ores. Characteristic assemblages containing heavy metals are also known to occur in sedimentary phosphate (uranium, cadmium) (Mar, Okazaki 2012). Other abiotic raw materials (building materials, industrial minerals) are usually significantly less critical as regards possible contamination with heavy metals. The solubility of heavy metals which are present in mining waste is increased by the tendency towards auto-oxidation.

Typical combinations are depicted in the so-called Reuter Metal Wheel (see Figure 5). This categorisation is based on the work of Professor Markus Reuter at the University of Melbourne. The illustration shows the typical assemblages of metals in ores and the forms in which they occur as sulphidic and oxidic ores. The concentric rings are also used to show which metals are typically the main component of ores, which metals are obtained as by-products, and which only occur as useless components.

There is a close relationship between the assemblages and the characteristics of the valuable minerals which were discussed in section 5.1.1, i.e. between the conditions of formation which were predominantly either oxidic or sulphidic and the respective assemblages of elements or minerals, which are shown in the wheel. With increasing distance from the centre, first the main metal, then secondary metals, trace elements, and finally accompanying elements which are of no interest economically, are shown. However, for the purpose of examining the ores as a source of heavy metals, whether or not the ore is of economic importance is irrelevant. In this context, substances are designated as heavy metals, if they are characterised by toxicity to animals and aerobic or anaerobic processes (Duffus 2001):

- As[13]
- Cd
- Cr
- Pb
- Hg
- Cu
- Ni
- Se
- Zn

Figure 5 Metal Wheel adapted from Reuter (amended by Wellmer and Hagelüken 2015)



It is recommended that mining for abiotic non-metallic minerals be rated as low hazard potential as regards associated heavy metals, unless there are indications that there may be a problem with heavy metals and/or arsenic.

The extraction of metallic raw materials is usually problematic to some degree as regards heavy metals and/or arsenic - as can be seen in Figure 5. So it is recommended that this be given a medium EHP rating.

13 Arsenic is included here, although as a semi-metal it is not altogether clear that it should be classified along with heavy metals.

Mining primarily for heavy metals, such as lead, mercury, cadmium, chromium, copper, uranium, and nickel, should be given a high EHP rating. This also includes mining for zinc ores, because these are almost always associated with lead ores.

5.1.3 Indicator 3: Assemblages containing radioactive substances

Minerals and mining waste often contain concentrations of uranium and/or thorium[14], which means that mining waste should be considered problematic as a (possible) source of radioactivity. This applies especially to ores and deposits of the following minerals: uranium, thorium, rare earths, tantalum, niobium, zircon, and sedimentary phosphates. However, experience in Germany and data from China have shown that higher concentrations may occur where other minerals are being mined or in particular deposits.

Assessment

Low EHP:

Raw material deposits normally exhibit low concentrations of uranium and/or thorium

Medium EHP:

Raw material deposits normally exhibit slightly higher concentrations of uranium and/or thorium.

High EHP:

Raw material deposits normally exhibit high concentrations of uranium and/or thorium.

Radioactive substances in mineral resources and processing residues are often the source of key environmental, health, and security problems in mineral extraction. As a general rule, the ionising radiation associated with mining is due exclusively to levels of uranium and thorium which are naturally present and which usually end up in processing residues[15] and may become more concentrated in the course of processing[16]. Other radioactive elements, such as radon gas, are products of the radioactive decay of uranium and thorium and may have a radiological impact via other pathways of exposure (inhalation). The occurrence of these elements is always dependent on the presence of uranium or thorium, so it is possible to make a reliable assessment on the basis of the concentrations of uranium and thorium in the mineral concerned.

As regards concentration levels which can be used in radiological assessment (to distinguish between a low and a medium EHP), the suggested minimum concentrations in ores or stored waste are 200 Bq/kg = 49 ppm for thorium and 300 Bq/kg = 24 ppm for uranium[17]. These concentrations are derived from the safe levels of gamma radiation (from the products of radioactive decay) which would

14 In the literature these are usually indicated using the abbreviation “NORM” (Normally Occurring Radioactive Material

15 Exception: When apatite is treated with sulphuric acid, the resulting phosphoric acid contains uranium, which is then taken up in the phosphate fertlisers which are produced from it. The products of radioactive decay (especially radium), however, end up in the phosphogypsum.
510g of gypsum are produced from the processing of 310g of phosphate ore, so the concentration of radium is reduced by a factor of 2.

16 This radioactive material which is concentrated in processing residues is also called TENORM (Technologically Enhanced Naturally Occurring Radioactive Material).

17 Council Directive 2013/59/EURATOM, ANNEX VIII: Definition and use of the activity concentration index for the gamma radiation emitted by building materials as referred to in Article 75

be exceeded if the gypsum were to be used as building material (in this case 1 mSv/yr). Below these levels of concentration, insulation of the ore or waste material is not required on radiological grounds[18]. Above these levels, the material has to be declared unsuitable for use where people are likely to be in close proximity for long periods or to be in contact with it (i.e. unsuitable for use as building material). People who stay on such uninsulated ground or flooring risk exposure to radiation of more than 1 mSv per year[19]. This discussion of limits was developed as part of the ÖkoRess project and another on-going project of the Öko-Institut (Deutschland 2049 - Auf dem Weg zu einer nachhaltigen Rohstoffwirtschaft)[20] on the basis of the specifications of the EU Guidelines 2013/59/EURATOM laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation[21] and international radiation protection standards.

Table 3 Reference levels for the radiological assessment of deposits

Assessment	Reference levels		Rationale
Low EHP	Reference level 1a: Th content [ppm] / 49 ppm + U content [ppm] / 24 ppm < 1	When U content and Th content are both known	Substrate may be used as building material, because this will not result in a risk of exposure to radiation greater than 1mSv per year.
	Reference level 1b: A_{Th} [Bq/g] / 0,2 Bq/g + A_U [Bq/g] / 0,3 Bq/g < 1	When activity concentrations (A) of both U and Th are known	
Medium EHP	Reference level 2a: Th content [ppm] / 246 ppm + U content [ppm] / 80 ppm < 1	When U content and Th content are both known and reference level 1a is >1	Substrate may not be used as building material, because this would result in a risk of exposure to radiation greater than 1mSv per year.
	Reference level 2b: A_{Th} [Bq/g] + A_U [Bq/g] < 1 Bq/g	When activity concentrations (A) of both U and Th are known and reference level 1b is >1	
High EHP	Reference level 2a: Th content [ppm] / 246 ppm + U content [ppm] / 80 ppm ≥ 1	When U content and Th content are both known	The substrate must be subjected to radiological monitoring in accordance with IAEA international safety standards.
	Reference level 2b: A_{Th} [Bq/g] + A_U [Bq/g] ≥ 1 Bq/g	When activity concentrations (A) of both U and Th are known	

A second, higher reference level (threshold for high EHP rating) is 1 Bq/g (or 1,000 Bq/kg). This is due to the fact that international radiation protection rules no longer permit the exemption of such

[18] The long-term storage of processing residues may still be required for other reasons, e.g. the concentration levels of non-radioactive components.

[19] In cases in which a mixture contains both thorium and uranium, the concentration levels must be combined in such a way that the combined dose of radiation from long-term exposure does not exceed 1 mSv per year (see formula in Table 3).

[20] See also: Buchert et al (2016)

[21] Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom

materials (exemption level) (IAEA 2014). The reference levels shown in Table 5, which are for use in the actual assessment, are derived from this.

Average activity concentrations of thorium and uranium are available for selected minerals in Chinese deposits (see Table 6). They show that Chinese deposits of vanadium, rare earths, niobium/tantalum, and zircon exhibit concentrations of Th and U which make a high EHP rating obligatory. The data also reveals that most of the other deposits exhibit concentrations of Th and U which preclude use of the material as building material.

If no specific data is available on activity concentrations or concentrations of Th or U, an assessment may be made using the following approximations:

- Uranium mining should always be given a high EHP rating[22]. For an ore to be worth mining, using existing technology and under current economic conditions, it must contain at least 0,03% uranium, which corresponds to 3,72 Bq/g. This is well in excess of both reference levels.
- Because uranium and thorium are typically associated with them, rare earths, tantalum, niobium, zircon, and sedimentary phosphates (including phosphates from the Sahara and from Florida) should always be given a high EHP rating.
- As shown in Table 6, one must assume that most of the other minerals in Chinese deposits are problematic as regards concentrations of Th and U. A medium EHP rating should therefore be assigned, if there is any doubt.
- The following minerals may be given a low EHP rating:
    1. Deposits of oxidic sediments (e.g. soapstone deposits in alluvial fans)
    2. Sedimentary rocks (e.g. limestone and sandstone)
    3. Basalt deposits
- Attention should nevertheless be paid to the following factors which could lead to a higher rating in exceptional cases at particular locations:
    1. When in contact with oxygen in the air, uranium in its hexavalent oxide form is slightly soluble in water, so uranium which may be present in oxidic sediments (e.g. alluvial fans) is usually washed out. However, the geochemical solution and transport of uranium oxide also leads to uranium often being deposited at deeper levels and/or displaced horizontally and then sometimes becoming enriched. Geochemical enrichment from a solution takes place especially in reducing layers of rock (e.g. in layers containing coal or pyrite). The concentrations in deposits are therefore homogenous only in exceptional cases.
    2. Additionally, some cobalt and gold deposits are known to be highly radioactive. These cobalt deposits are in parts of Katanga (Democratic Republic of Congo). (Tsurukawa et al 2011) The gold deposits are in parts of South Africa. (Durand 2012)

[22] Mining of thorium is not considered because it is not practised due to the low price on the world market and the level of existing stocks.

Table 4 Average activity concentrations of U and Th in Chinese deposits and assessment of corresponding ratings

Mineral	A_{Th} [Bq/g]	A_U [Bq/g]	Reference level 1 (boundary between low and medium EHP)	Reference level 2 (Boundary between medium and high EHP)	EHP rating	China's share of world production (2013)
Vanadium	27.0	1.036	138.5	28.036	High	51.9 %
Rare earths	5.782	3.972	42.2	9.754	High	86.4 %
Niobium/Tantalum	2.015	4.476	25.0	6.491	High	Nb: <2 %, Ta: 5.1 %
Zircon	1.733	1.289	13.0	3.022	High	9.9 %
Aluminium (bauxite)	0.240	0.482	2.8	0.722	Medium	16.3 %
Lead/zinc	0.069	0.649	2.5	0.718	Medium	Pb: 52.8 %, Zn: 37.3 %
Coal	0.051	0.383	1.5	0.434	Medium	data not available
Phosphate	0.026	0.396	1.5	0.422	Medium	48.0 %
Tin	0.133	0.218	1.4	0.351	Medium	37.4 %
Iron	0.068	0.270	1.2	0.338	Medium	46.6 %
Coal (gangue)	0.082	0.171	1.0	0.253	Medium	data not available
Copper	0.034	0.142	0.6	0.176	Low	8.7 %
other	0.508	0.503	4.2	1.011	High	data not available

Sources: Hua 2011, USGS 2015

5.2 Technology Level

Both the environmental hazard potential and the extent of environmental destruction resulting from mineral extraction depend to a large extent on two technical processes:

- the method of mining/extraction;
- the methods of processing and the auxiliary chemicals or reagents used.

These are often determined by the nature of the deposit, geological factors, and the mineral. Nevertheless, mining companies have some (limited) leeway at the level of individual mining sites, e.g. as regards the preference for deposits where opencast mining is possible (which promises economic advantages) over deposits which necessitate underground mining. Where processing is concerned, there may also be legal hurdles, e.g. laws in Alaska and Siberia, which ban the use of amalgamation in the processing of gold and are strictly enforced. When a particular raw material is being assessed, the commonly used methods of extraction and processing have to serve as the basis for the assessment of environmental hazard potential.

5.2.1 Indicator 4: Method of extraction

The method of extraction used in mining provides an indication of the extent of disruption of the Earth's surface which is necessitated by extraction of the mineral. It is in the nature of underground mining that there is the least disruption of the natural environment. The former Käfersteige (fluorspar) mine near Pforzheim was a prime example of this. Only two surface openings (an entrance/exit for miners and an opening for ventilation) were the only signs of mining activity. Where opencast mining (quarrying, ore extraction) is concerned, the disruption is usually limited to an area which is not much larger than the area where the deposit is at the surface. In addition to this, part of the mine or quarry is often used for waste storage, which further reduces the area required for spoil heaps and mine tailings. The most disruption is caused by the mining of unconsolidated sedimentary deposits (alluvial and colluvial deposits) not only for minerals such as gold, diamonds, tin, titanium sands, etc., but also for lignite or bauxite. This criterion is therefore regarded as an indicator for area of land used and destruction or disruption of ecosystems.

Assessment

Low EHP:

Mineral is usually extracted from underground mines

Medium EHP:

Mineral is usually obtained through opencast mining of solid rock, using mining techniques (drilling and blasting) or other methods of loosening the rock.

High EHP:

Mineral is predominantly obtained from unconsolidated sedimentary deposits (alluvial and colluvial deposits), which can be extracted without loosening the rock beforehand.

The choice of extraction methods for individual minerals depends on the geological parameters of deposits and also on the technical preferences of mining companies and fashions in technology. Given the diverse nature of individual mining sites, it is necessary to make generalisations regarding standard, i.e. commonly used, mining techniques. These generalisations should cover the various types of deposits of a particular mineral and the various extraction methods. While there is little variation in the deposits of minerals such as phosphates and lead/zinc, there is great diversity in the case of gold, for example. This mineral is extracted from alluvium, occurs in massive ores or gangue ores, and is extracted by dredging or traditional mining. The following table shows the standard methods of extraction; The extraction methods which are shown in bold are those which are globally predominant.

Table 5 Summary of extraction techniques for individual minerals

Mineral	Method of extraction
Antimony	**Underground mining**
Aluminium	Not mined as such → see bauxite
Barite	**Opencast mining of solid rock,** Underground mining
Bauxite	**Opencast extraction of unconsolidated rock**
Bentonite	**Opencast extraction of unconsolidated rock** (Johnstone (1954):78)
Beryllium	**Opencast mining of solid rock**
Borate	**Extraction from brine**, mining of solid rock, e.g. kernite (Johnstone (1954): 94ff.)
Chromium	**Underground mining**
Diatomite	**Opencast extraction of unconsolidated rock**
Iron ore	**Opencast mining of solid rock**
Feldspar	**Opencast mining of solid rock,** Underground mining
Gallium	By-product of production of aluminium from bauxite. Smaller quantities obtained from zinc extraction (Nassar et al (2015)).
Germanium	60% as a by-product of zinc production. 40% as fly ash from coal combustion (Nassar et al (2015)).
Gypsum	**Opencast mining of solid rock**
Gold	**Opencast mining of solid rock**, underground mining of lode ores, extraction of alluvium
Graphite	**Underground mining**
Hafnium	**Extraction of alluvium,** beach placer deposits of zircon
Indium	By-product: 80% from Zn ore, 15% from Sn ore, 5% from Cu ore (Nassar et al (2015)).
Potassium salt	**Underground mining**
Limestone	**Opencast mining of solid rock**
Kaolin & kaolinite	**Opencast extraction of unconsolidated rock**
Cobalt	**Opencast mining of solid rock,** underground mining
Coking coal	**Opencast mining of solid rock,** underground mining
Copper	**Opencast mining of solid rock,** Underground mining
Lithium	**Extraction from brine in salt lakes (ca. 52%),** 48% from pegmatites (Nassar et al (2015))
Magnesite	**Opencast mining of solid rock**
Magnesium	Not mined (Taggart (1953): 2 -198), electrolysis
Manganese	**Opencast mining of solid rock,** underground mining
Molybdenum	54% from Mo ore, 46% as by-product of copper extraction (Nassar et al (2015)), **opencast mining of solid rock**
Nickel	**Opencast mining,** underground mining
Niobium	**Opencast mining of solid rock,** underground mining
Perlite	**Opencast mining of solid rock**
Quartz sand	**Opencast extraction of unconsolidated rock**
Rhenium	By-product: 71% from Cu-Mo ores, 29% from Cu ores (Nassar et al (2015))
Scandium	By-product of production of titanium
Selenium	By-product: 90% from Cu ores, 10% from other ores (Ni/Zn, Ag/Hg, Pb) (Nassar et al (2015))
Phosphates	**Opencast extraction of unconsolidated rock**
Platinum group metals (PGM)	**Underground mining**, dredging (Taggart (1953): 2-219)

Mineral	Method of extraction
Rare earths	**Opencast mining of solid rock** (Bouorakima (2011))
Silver	**Opencast mining of solid rock,** underground mining
Silicon	Not mined as such → see Quartz sand
Talc	**Opencast mining of solid rock,** underground mining
Tellurium	By-product: 90% from Copper ores, 10% from Pb and Bi ores (Nassar et al (2015)).
Tantalum	**Opencast mining of solid rock**
Titanium	**Extraction of alluvium,** beach placer deposits of ilmenite
Vanadium	**Opencast mining of solid rock,** underground mining
Tungsten	**Underground mining**, opencast mining
Zinc	**Underground mining**
Tin	**Extraction of alluvium,** beach placer deposits, underground mining

5.2.2 Indicator 5: Use of auxiliary chemicals

During extraction and processing, auxiliary chemicals, lubricants, and cooling or heating fluids are used which may be toxic or otherwise harmful to the environment. If they are released into the environment, this can lead to negative environmental impacts. This indicator therefore shows the potential environmental impact of auxiliary chemicals (including lubricants and cooling/heating fluids), which are a danger to the environment, and is intended to complement the indicator for geogenic environmental hazard potential arising from mineral assemblages. When assessing ratings for this indicator, it is necessary to take into account the consequences of possible accidents as well as the normal operation of mining and processing, which - especially in the case of industrial mining facilities - is controlled by environmental management systems (risk analysis, definition of responsibilities, lines of communication, job descriptions, and prescription of protective measures). Many of the problems associated with mining, which are the subject of public debate, and many social conflicts are sparked off by accidents.

Assessment

Low EHP:

Auxiliary chemicals are not normally used in extraction and processing (e.g. gravity separation or optical or magnetic separation)

Medium EHP:

Auxiliary chemicals are often used in extraction and processing (e.g. in flotation)

High EHP:

Leaching and/or amalgamation are often used in extraction and processing.

Methods of extraction and processing, classified according to the technical processes conventionally used in mining and processing, are listed here. They are intended to serve as a guide for classification - for the purpose of assessment - of the processes used at individual mining/processing sites.

To obtain a rating for this indicator for a particular raw material, the most commonly used process is identified and a low, medium, or high EHP rating is assigned according to the criteria outlined above. The commonly used processes and their application in the processing of particular minerals are summarised in Tables 6 and 7.

Table 6 Summary of standard processes

	Extraction	Processing
Without auxiliary chemicals	Mechanical loosening and loading of rock (including drilling and blasting)	Purely mechanical treatment processes (simple gravity separation, selective comminution) Optical separation Hand picking Electrostatic processing Hot-cold dissolution process
With auxiliary chemicals	-	Heavy media separation using FeSi Bioleaching, thiourea leaching Diamond processing on grease tables
With toxic auxiliary chemicals	In situ leaching	Amalgamation in processing of gold (using mercury, which should no longer be used at all according to the Minamata Convention) Cyanide leaching and chlorination (Both are very toxic substances, which have often been involved in accidents.) Solvent extraction Flotation (usually using long-chain (organic) hydrocarbons which are highly toxic and not easily degradable)

Table 7 Summary of processes most commonly used in processing of particular minerals

Mineral	Standard method of processing	Source:
Aluminium	*Not mined as such*	
Antimony	Flotation	Taggart 1953: 2-20
Barite	Heavy media separation, gravity separation	Johnstone 1954: 70
Bauxite	Leaching, rotary kiln	Taggart 1953: 2-19; European Commission 2014: 379
Bentonite	Acid digestion	Johnstone 1954: 78
Beryllium	Hand picking	Taggart 1953: 2-21
Borates	Flotation	Johnstone 1954: 94 ff
Chromium	Heavy media separation, gravity separation	Taggart 1953: 2-23
Diatomite	Dewatering	Johnstone 1954: 160
Iron ore	Flotation, magnetic separation	Taggart 1953: 2-138 to 2-145
Feldspar	Hand picking, flotation, gravity separation, froth flotation	Johnstone 1954: 166, 173
Gallium	*Obtained as a by-product of aluminium production from bauxite (according to Hagelüken)* *By-product of zinc production*	Taggart 1953: 2-69 Johnstone 1954: 192-193
Germanium	*Obtained as a by-product of zinc production*	Taggart 1953: 2-70 Johnstone 1954: 192-193
Gypsum	Calcination	Johnstone 1954: 211
Gold	Leaching with cyanide, amalgamation, gravity separation	Taggart 1953: 2-71 to 2-75

Mineral	Standard method of processing	Source:
Graphite	Flotation, magnetic separation, electrostatic separation	Johnstone 1954: 197
Hafnium	Magnetic separation, flotation	Taggart 1953: 2-254
Indium	*Obtained from ores which are oxides or sulphides of zinc*	Taggart 1953: 2-133
Potassium salt	Hot-cold dissolution process, electrostatic separation, flotation	Johnstone 1954: 410 ff
Limestone	Calcination	Johnstone 1954: 246
Kaolin & kaolinite	Selective extraction, hydrocyclones used in production of finest kaolin	
Cobalt	Roasting, acid digestion	Taggart 1953: 2-25
Coking coal	Gravity separation, flotation, cyclone, coke oven	NCEP 2008: 106 ff
Copper	Flotation, solvent extraction, (1) when ore highly concentrated, >6%, immediate smelting; (2) flotation followed by electrolysis; (3) concentration, roasting, reverberatory furnace Bioleaching for processing of spoil	Taggart 1953: 2-28 European Commission 2014: 197 Neale 2006: 1
Lithium	Condensation of solutions	Johnstone 1954: 276
Magnesite	Calcination for production of fireproof materials	Johnstone 1954: 291
Magnesium	*Not mined* Electrolysis	Taggart 1953: 2-198
Manganese	Log washing, hand picking	Taggart 1953: 2-199 ff
Molybdenum	Gravity separation, flotation, calcination	Taggart 1953: 2-210
Nickel	Flotation, roasting, magnetic separation, calcination	Taggart 1953: 2-213 European Commission 2014: 893
Niobium	Flotation (roughing and cleaning flotation with addition of silicofluorides)	Bulatovic 2010: 119
Perlite	Hot-cold dissolution process	Johnstone 1954: 381
Phosphates	Acid digestion, sometimes flotation to separate out impurities, drying	Johnstone 1954: 384 ff
PGM	Amalgamation, roasting, leaching	Taggart 1953: 2-219
Quartz sand	Hydrocyclone	Grigoriva & Nishkov 2012: 2
Rhenium	*Obtained from metallic dust from production of molybdenum* Asbestos filters, electrostatic precipitation	Johnstone 1954: 415
Scandium	Leaching, solvent extraction	Mitacs 2015
Selenium	*Obtained from anode mud produced during production of copper* Amalgamation Roasting, acid digestion	Johnstone 1954: 427 Johnstone 1954: 428 Taggart 1953: 2-220
Rare earths	Flotation, physio-chemical separation, roasting, carbonate precipitation, acid leaching, solvent extraction	Hurst 2010 Bouorakima 2011
Silver	Flotation, cyanide leaching	Taggart 1953: 2-130
Silicon	*Not mined*	
Talc	Dissolved air flotation	Johnstone 1954: 493
Tantalum	Gravity separation	Taggart 1953: 2-221

Mineral	Standard method of processing	Source:
Tellurium	*Obtained from anode mud produced during production of copper; by-product of copper production* Amalgamation	Johnstone 1954: 427 Taggart 1953: 2-222 Johnstone 1954: 428
Titanium	Gravity separation, magnetic separation, leaching, acid-base separation	Johnstone 1954: 570
Vanadium	Hand picking, leaching, flotation	Taggart 1953: 2-253 Johnstone 1954: 614
Tungsten	Gravity separation, flotation	Taggart 1953: 2-244
Zinc	Flotation, roasting, leaching	Taggart 1953: 2-153 European Commission 2014: 603 ff
Tin	Gravity separation	Taggart 1953: 2-225

5.3 Natural Environment Level

Indicators 6-8 for the Natural Environment level give an indication of the possible environmental hazard potentials (at mining sites). These indicators were developed for the site-related assessment and are described briefly here. For each of these indicators, it has been possible to identify publicly available maps of risks and protected areas - global data which is available for download in map form or as digital data. This makes it possible to make independent site assessments. These indicators have been used as a basis for the raw material related assessment (see sections 5.3.4 to 5.3.6).

5.3.1 Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides

There are four indicators which can be used for assessment in relation to the goal "prevention of accidents induced by natural events". These are: earthquake risk; landslide risk; tropical storm risk; and flood risk. Using the risk maps available, it has been possible to award low, medium, or high hazard potentials.

The assessment of earthquake risk is based on the global data of the Global Seismic Hazard Assessment Programme (GSHAP). The hazard potential for a particular region is assessed on the basis of the peak ground acceleration (PGA) which has a 10% probability of being exceeded within the next 50 years.

Where the risk of landslides is concerned, use is made of the data on dangerous areas from the Global Assessment Report on Disaster Risk Reduction 2013 (UNISDR 2013). Use is made in particular of the risk map for downward movements of masses of earth (soil, rock, and other materials) induced by precipitation[23].

The risk of tropical storms is assessed using the risk map in the Global Assessment Report on Disaster Risk Reduction (UNISDR 2015a). A time frame of 100 years was chosen for the expected peak wind speed.

The risk of flooding is assessed on the basis of data from the Global Assessment Reports 2015 (UNISDR 2015b) on the risk of flooding due to a river overflowing. A time frame of 100 years was chosen. The risks have not been categorised. If a measurable level of flooding is expected, the hazard potential is designated as high (red).

[23] Downward movements of masses of earth, etc. triggered by earthquakes are covered sufficiently by the "earthquake risk" indicator.

In principle it is possible to make a global assessment of these four indicators, except that the Arctic is not covered. There is no global data available on the risk of accidents due to the following specific natural events: polar storms; flooding due to snow melt[24]. In accordance with the precautionary principle, the rule was established that the risk of accidents induced by natural events at locations in the Arctic be given a medium (yellow) accident potential rating.

5.3.2 Indicator 7: Water stress index and arid regions

In order to assess attainment of the goal "prevention of water conflicts", the "water stress index" (WSI) (Pfister et al, 2009) was used as an indicator initially. This is based on the WTA (Withdrawal to Availability), which measures the quantity of freshwater withdrawn as a proportion of the quantity of water available from renewable sources. The WTA was weighted to take account of seasonal variations and then converted into the WSI using a logarithmic function. Pfister et al (2009) set the boundary between moderate and severe water stress but not between low and moderate water stress. Germany was used as the benchmark for this latter boundary. The WSI for mining sites is calculated using the Google Earth™-Layer published by Pfister et al (2009), which gives the WSI at catchment area level.

As a measure of water withdrawn in relation to the quantity of water available, the WSI does not indicate arid areas sufficiently, because there may not be any measurable withdrawal of water in such areas. Additional account has therefore been taken of arid regions. As a general rule, sites in arid regions have been awarded a high (red) hazard potential.

5.3.3 Indicator 8: Designated protected areas and AZE sites

In order to ensure that valuable ecosystems are protected and maintained, it is desirable to have an indicator which highlights all the ecologically sensitive areas which need to be protected. This would require data to be globally accessible, however. As a minimal approach, existing officially designated protected areas have been selected as an indicator. This includes, for example, the UNESCO world heritage sites designated by the World Heritage Convention and protected areas which are part of the IUCN (International Union for Conservation of Nature) global protected areas programme. Officially designated protected areas are documented in a global database, the World Database on Protected Areas (WDPA), which is publicly available.

Hazard potentials have been assessed using the process in the draft standards of the Initiative for Responsible Mining Assurance (IRMA). "Highly protected areas", which are designated as "no-go-zones", are given a high (red) hazard potential. And "protected areas" are awarded a medium (yellow) hazard potential. These "protected areas" are to be treated as exceptional: Exploration and extraction are allowed, only so long as the activities, which may include provision of compensation, are in accordance with the protection goals of the protected areas. To complete the process, AZE sites[25] were included in the assessment for ÖkoRess and awarded a medium hazard potential.

All the (site) indicators can be assessed using world maps. In the course of the project - and with a view to making the transition to a raw material related assessment - a GIS system of evaluation was developed.

[24] Flood risks can only be assessed between the latitudes of 60 degrees north and 56 degrees south, because geographical coverage of input parameters for computer modelling is limited.

[25] Areas designated by the Alliance for Zero Extinction (AZE), in which at least one species which is threatened with extinction has been recorded.

5.3.4 Some approaches to raw material related assessment

In principle, a raw material related assessment of risks at mining sites requires an approach which allows general statements to be made about individual raw materials. This in turn means that one has to know where minerals are produced in order to then be able to estimate the extent to which a particular mineral is extracted in areas with higher site risks. Copper, for example, due to its geogenic origins, occurs mostly in earthquake zones, so it can generally be assumed that there is a relatively high risk of accident due to earthquakes. There are basically two approaches to estimating site risk for individual raw materials:

1. Evaluation of country data;
2. Evaluation of georeferenced mine data.

Both these approaches - and their advantages and disadvantages - are described in the following two sections. But in any case, the purpose of raw material related assessment of site risks is to make it possible to establish whether - due to the conditions in mining areas - the extraction of a particular raw material is generally associated with a low, medium, or high environmental hazard potential (EHP). Limits or boundaries (between low, medium, and high EHP) need to be set in order to complete a ratings matrix. These have not yet been set in Table 2, so they are represented by the variables >X% and >Y%.

It is not possible to set these limits - the percentage above which the active extraction of a raw material is associated with a medium or high EHP for the natural environment - empirically. These limits can only be set by means of value judgements. In this assessment, a low EHP rating is awarded if the percentage is below the set limit. Otherwise a medium or high EHP rating is awarded, if the relevant limit is exceeded.

At this point in time the authors have consciously chosen clear limits or boundaries for this initial approach to assessment. Provisional rules, such as “medium EHP when half the limit for high EHP is exceeded”, were discussed and will be taken up in the successor project, Ökoress II (FKZ 3715 32 310 0). No suggestions will be made as regards the setting of limits until this can be done as part of ÖkoRess II, because the assessment of the 51 raw materials in the EU study (EU Commission 2014), which is to be undertaken in ÖkoRess II, is needed to provide adequate data for orientation.

The following approaches to the setting of limits could be used in combination:

1. Orientation on the basis of mathematical parameters, such as the mean, median, percentile, and variance of measurements.
2. Expert evaluation or orientation on the basis of tendencies in the way things are developing, social norms/values, etc.

After weighing up the pros and cons, the decision was made to use georeferenced mine data (section 5.3.6) for both the possible approaches to the assessment of raw materials outlined below, because such data is more precise than country data (section 5.3.5). In an ideal situation, in which comprehensive data would be available, spatial evaluation of the indicators would be as valid as a comprehensive survey.

5.3.5 Evaluation using country data

Evaluation using country data is a simplified approach to raw material related assessment of the risks associated with mining. In principle, it is possible either to use existing country indicators of the degree of risk posed by mines or to calculate country values using ÖkoRess I project data.

Evaluation using country data is only possible, if it is known where raw materials come from. Country production figures were compiled by project-consult using relevant sources of data (USGS, BGS, BGR). Figure 6 shows an overview of the raw materials bauxite, copper, gold, graphite, and tungsten. These minerals were selected for the evaluation of the approaches to raw material related assessment.

Figure 6 Production figures by country

Rohstoff	Argentinien	Australien	Bosnien Herzogovina	Brasilien	Bulgarien	Chile	China	Ghana	Griechenland	Guinea	Guyana	Indien	Indonesien	Jamaika	Kanada	Kasachstan
Bauxite		34,0	0,3	16,4			17,5	0,2	1,1	8,5	0,9	6,3		4,9		2,7
Copper	0,9	5,4		1,3	0,7	33,9	7,5						5,5		3,3	
Gold		9,8		2,4		1,7	13,7	3,3					3,6		4,0	1,4
Natural graphite				7,0			68,0					14,0			3,0	
Tungsten							85,0								1,0	

Rohstoff	Marokko	Mexiko	Papua Neuguinea	Peru	Polen	Portugal	Russland	Sambia	Schweden	Südafrika	Suriname	Türkei	USA	Usbekistan	Venezuela	Sonstige	Abgebildete Gesamtproduktion
Bauxite							2,9				1,6	0,4			1,2	1,1	98,9
Copper	0,1			7,8	2,6	0,5	4,4	4,3	0,5			0,6	6,9			13,8	86,2
Gold		3,3	2,2	6,2			7,2			7,1			9,1	3,5		21,5	78,5
Natural graphite																8,0	92,0
Tungsten					2,0		4,0									8,0	92,0

Source: Compiled by projekt-consult

The sums of the percentages of annual global production produced by the main producing countries listed here range from 78.5% (gold) to 98.9% (bauxite) of global production. The aim is to account for at least 75% for the ÖkoRess II project (FKZ 3715 32 310 0). In order to calculate the raw material related risks from mining, it is necessary to divide the figures for each country by that country's annual production of the raw material and then to add the resulting figures together.

The major disadvantage of this approach is that the aggregation of local data into country figures is very unrepresentative, especially when natural hazard potentials are unequally distributed within a country. The figures tend to become increasingly meaningless as the size of the country increases. Furthermore, mines are not evenly distributed across a country and are not necessarily either inside or outside danger zones.

It is altogether questionable whether the indicators are generally meaningful, if firstly the local hazard potentials and secondly the production figures are only aggregated at the country level.

5.3.5.1 Existing country data

Available country-by-country values, such as the World Risk Index (WRI) and the Disaster Risk Index (DRI) combine various risks resulting from exposure to natural dangers. In principle, one advantage of these publicly available indices is that they have been created in a social context and are used by international institutions such as the World Bank. However, these indices contain - as is usual for the purposes of risk assessment - not only the hazard potentials (probability of a dangerous event occurring), which are of interest for this project, but also the degree of harm which is to be expected (usually the number of deaths).

The World Risk Index (WRI) is calculated as the product of the risk due to exposure to natural dangers and the vulnerability of the society which is affected[26]. The index therefore answers the question: Which parts of the world have the greatest disaster risk from an anthropocentric point of view? It shows where natural disasters impact on a vulnerable society. The index states, for 171 of the world's countries, the risk of being affected by a disaster as a result of extreme natural events.

[26] http://weltrisikobericht.de/

The Disaster Risk Index (DRI) also serves an analogous purpose. It allows calculation, by country, of the average risk of death as a result of a disaster due to an earthquake, a tropical cyclone, or flooding. In comparison with the WRI, the DRI has been calculated on the basis of older data, however. The data used is from 1980-2000[27].

Simply the fact that these existing indices include the degree of harm expected in the case of a disaster occurring means that they are only of very limited usefulness for a raw material related assessment. In addition to this, the indicators on which the indices are based are not specially tailored to the question of hazard potentials for areas where abiotic raw materials are extracted.

5.3.5.2 Project related country data

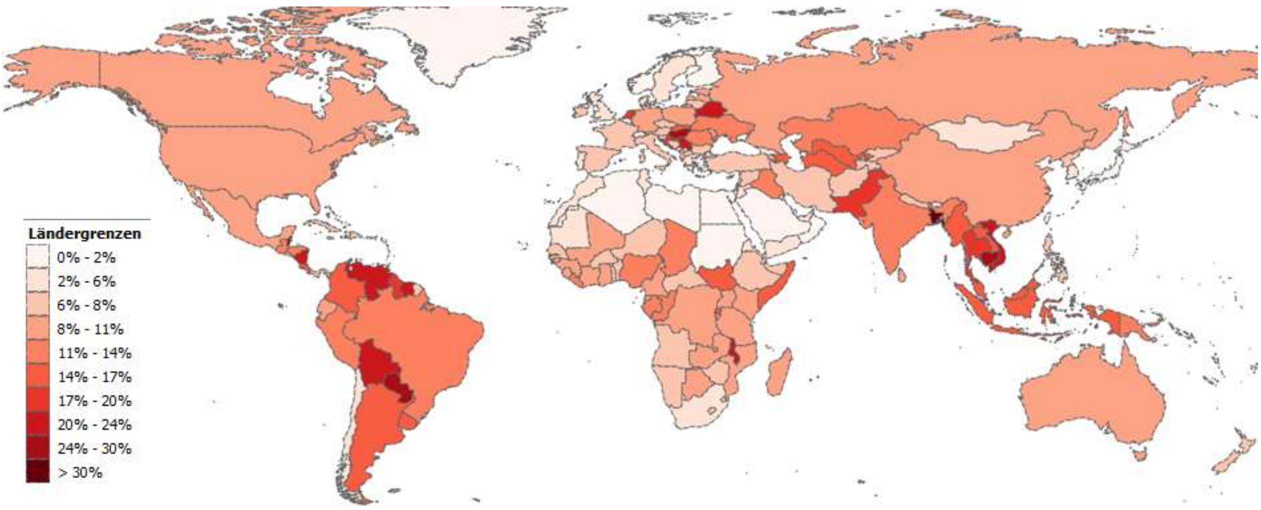
It is possible to calculate project related country figures/values using the results of site related assessments. The indicators which have been developed for this purpose (see section 5.3.1) are based on risk maps similar to those used for the calculation of the WRI.

The development of our own indicators for site related assessment was a consequence of the lack of a suitable publicly available index which could present a comprehensive picture of the hazard potentials of mining sites. The derivation of country values is therefore also preferable to the use of existing indices, where a raw material related assessment is concerned.

Country values can be derived from frequency distributions at country level. For each of the three indicators it is possible to determine the frequency or proportion of the total area of a country which has a medium (yellow in the site related assessment matrix) or high (red in the site related assessment matrix) hazard potential.

The graded distribution of areas susceptible to flooding worldwide is shown in Figure 7 as an example. Aggregated country values can be calculated in the GIS using all the available UNEP risk maps and the measurement guidelines for site related assessment.

Figure 7 A graded illustration of the proportion of each country's area which is susceptible to flooding (percentage)



Sources of data: USGS; Cartography: ifeu.

[27] http://www.undp.org/content/undp/en/home/librarypage/crisis-prevention-and-recovery/reducing-disaster-risk--a-challenge-for-development.html

5.3.6 Evaluation using georeferenced mine data.

In an ideal world as regards data availability, in which there were both georeferenced data for mining sites and production figures for those sites, a spatial assessment of the indicators for the "natural environment" of mining areas would be as valid as a comprehensive survey. This would be possible because the indicators in the site related assessment matrix could be calculated for each and every individual mining site. The results of such an evaluation would reflect the overall picture. Precise observations could then be made, such as:

> "Thirty percent of the annual production of the raw material comes from areas with a low hazard potential for naturally induced accidents"
>
> "Forty percent of the annual production of the raw material comes from areas with a medium hazard potential for naturally induced accidents"
>
> "Thirty percent of the annual production of the raw material comes from areas with a high hazard potential for naturally induced accidents"

It would be possible to generate world maps for each raw material, which show the mines according to volume of production and the values of the indicators for "risk of naturally induced accidents", "water stress and arid areas", and "designated protected areas and AZE sites". It would also be possible to calculate future environmental hazard potentials, if georeferenced data were available for reserves.

This approach to assessment therefore has great potential as a means of ascertaining both current and future environmental hazard potentials of areas where abiotic primary raw materials are extracted. Among all the data available there is currently no ideal collection of data on mining sites or deposits. Nevertheless, there is enough data of sufficient quality to make the assessment of site risks using georeferenced mine data significantly more advantageous than an approach using country data.

Section 5.3.6.1 contains an overview of the currently available data, including the databases which were selected as the basis for the assessment. The process of assessment is outlined in section 5.3.6.2 and the results of the evaluation are shown in section 5.3.6.3.

5.3.6.1 Currently available data

Broad searches for publicly available collections of data on mining sites show that there is currently no ideal set of data. The data which are available for purchase from consultancies are not suitable for evaluation as part of the ÖkoRess projects, because on the one hand they are very expensive and on the other hand they do not include raw data. The following institutions (among others) sell data on mining:

- SNL Metals and Mining database, SNL Financial Ltd[28] (source of data for WWF study[29])
- DrillingInfo database, DrillingInfo inc[30] (source of data for WWF study).

Official data collections which are most suitable for spatial analysis of raw material related data are made available by the US Geological Survey (USGS). Large quantities of geodata related to mining are available on the "Mineral Resources On-Line Spatial Data" platform (http://mrdata.usgs.gov/). As a

[28] http://www.snl.com/Sectors/metalsmining/Default.aspx (last accessed on 03.06.2016)

[29] WWF/Aviva/Investec 2015: Safeguarding Outstanding Value http://assets.wwf.org.uk/downloads/wwf_nwh_investor_report_a4_web_v2_1.pdf?_ga=1.94245341.1318832012.1473063270

[30] http://info.drillinginfo.com/products/di-geodata-services/ (last accessed on 03.06.2016)

general rule, USGS primarily publishes data for the United States, but there is also a certain amount of global data. The following global data collections were investigated more closely for this project:

- Mineral Resources Data System (MRDS)
- Major mineral deposits of the world
- Mineral operations outside the United States.

These and other geodata from USGS are described in greater detail in the appendix (section 12.1). Table 8 provides an overview of the advantages and disadvantages of the three main USGS geodata collections.

Table 8 Comparison of selected publicly available USGS geodata collections

Data collection	Advantages	Disadvantages
Mineral Resources Data System (MRDS)	- large number of cases (>300,000) - wide range of raw materials	- no production figures - no spatial dimensions given - USA over-represented - last partially updated in 2011
Major mineral deposits of the world	- significant deposits throughout the world	- only 11 raw materials - no quantities given - no spatial dimensions given
Mineral operations outside the US	- 6,477 data sets - includes production figures	- significantly fewer datasets than MRDS - coordinates appear to be inaccurate - production figures are often totals for an entire country (“combined capacities for ...”)

The MRDS data collection was selected as the basis for the assessment, because this collection of data has the largest number of cases and none of the other collections contains comprehensive data on production figures. Although the “mineral operations outside the US” data collection contains production figures, it encompasses “only” about 6,500 data sets. And in many cases the production figure for a country as a whole (“combined capacities for ...”) is given instead of production figures for each individual mine. Alternatively figures may be an expert’s estimates.

5.3.6.2 Analysis and evaluation of the data

The selected MRDS data collection includes a very large number of cases but no production figures. The production figures are significant, however, because they are a measure of the importance of the mines. The country production figures (Figure 6) are used for the evaluation as the best possible approximation using the available data. The evaluation process as a whole can be divided into the following three steps:

1. Evaluation of data on mines
2. Focus on main producing countries (Figure 6)
3. Weighting of mine evaluation results according to main producing countries’ shares of total production

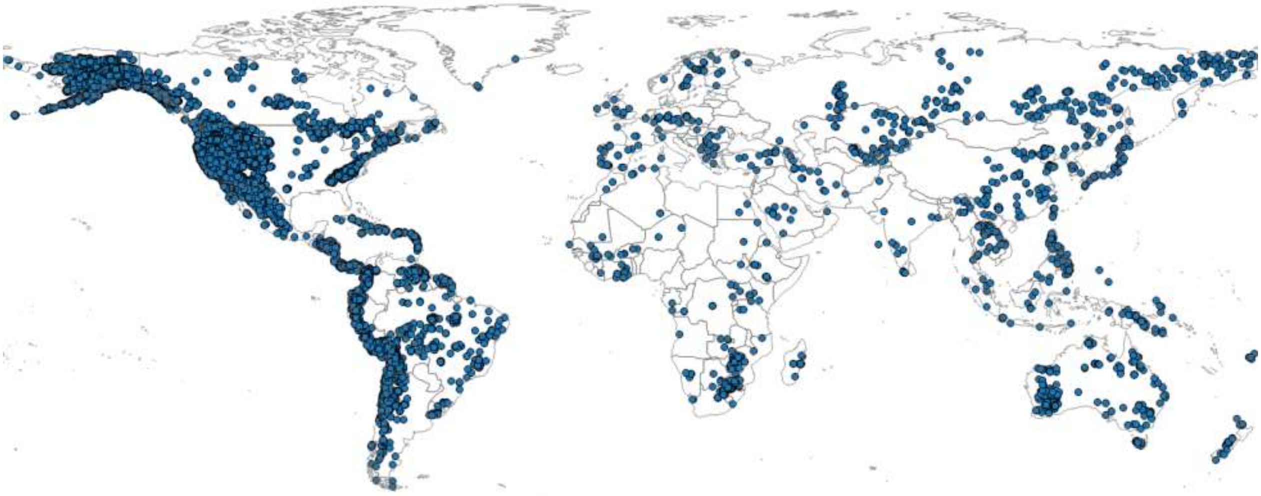
Each of these steps was carried out separately during the course of the project, in order to be able to evaluate the resulting changes in the frequency distribution of a raw material (proportions of low, medium, and high hazard potential according to the measurement guidelines for the site related assessment). The aim was to ascertain whether a simplified analysis - without taking producing countries or country production figures into account - would be sufficient. The results showed, however, that the weighting step brought about significant changes in the distribution, which means that this step is essential.

Evaluation of data on mines

The first step, i.e. the evaluation of the MRDS data on mines, was to filter the data according to the entries in the three "Commodity" fields and the "Development status" field. In the case of "Development status", cases (i.e. sites) were only considered, if the entry (in the "Development status" field) was "producer" (active mine) or "prospect" ("beyond occurrence stage", in the pipeline). The purpose of this was to include as high a number of cases as possible. As a result, potential future mines were included as well, in the knowledge that only a fraction of these deposits will actually be developed, according to mining experts. Scrutiny of the number of cases which are "producer" or "prospect" sites for the five raw materials which we are considering here showed that there are enough "producer" entries, so that it is not necessary to include "prospect" sites in order to increase the number of cases. Further checks will be carried out for the 51 raw materials in the course of ÖkoRess II. The field entries "occurrence", "past producer", "plant", and "unknown" will definitely not be included.

In the case of gold, Figure 8 shows the geographical distribution of the mines and deposits which were included in the analysis. As is generally the case with the MRDS data collection, mine data for the USA are over-represented. For the purpose of calculating indicators for the natural environment, it was assumed that all the mines extended over 500m. This may be an underestimate of the actual extent of mines. In the 40 case studies, the extent of the mines was found to vary from 1 km to 400 km. For the assessments which are to be part of the ÖkoRess II project, a figure for the extent (of mines) will be established for each raw material instead of applying the same figure across the board. So, for example, where the extraction of copper, gold, and bauxite is concerned, mines are usually large, so that an extent of 10 km can be assumed. The extraction of tungsten and graphite on the other hand tends to be in smaller mines, for which an estimated extent of 500 m would be appropriate.

Figure 8 MRDS data on gold mines



Source of data: USGS; Cartography: ifeu.

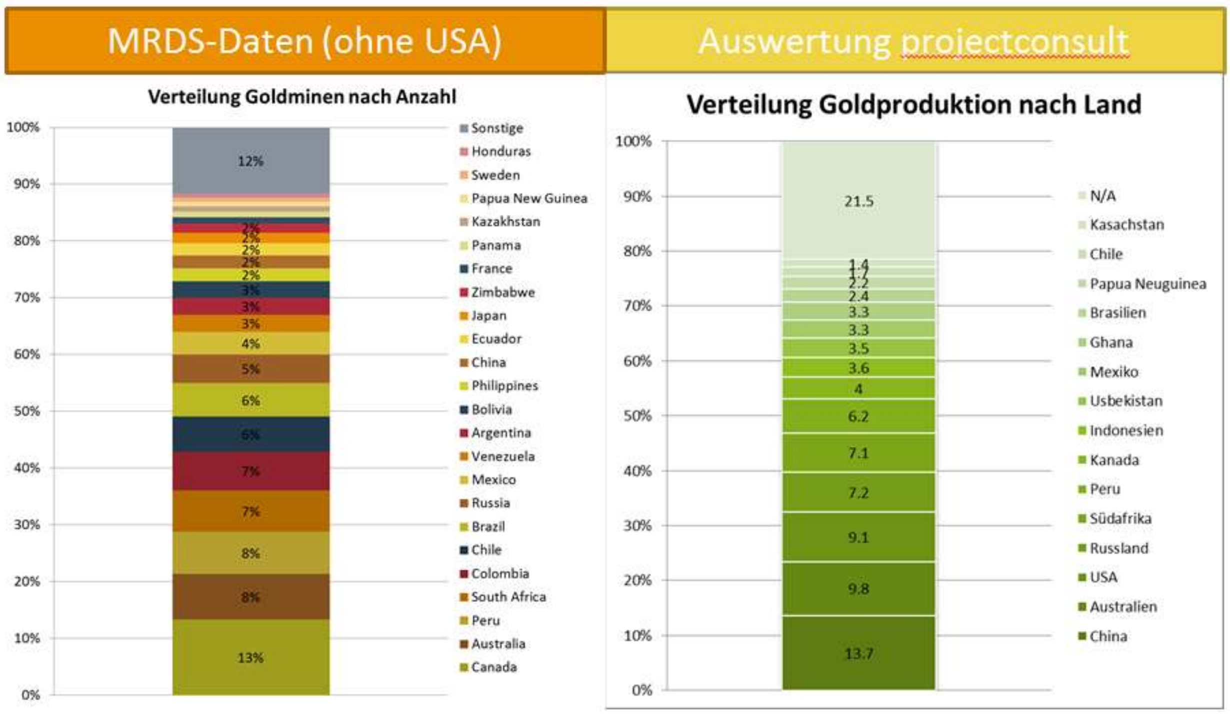
The results of the evaluation provide frequency distributions (low - medium - high, according to the measurement guidelines for the site related assessment) for the indicators "risk of naturally induced accidents", "water stress and arid areas", and "designated protected areas and AZE sites" at the MRDS mines. The importance of the mining sites, in terms of volume of production, is not accounted for.

Focus on main producing countries

As a second step, in order to take account of the importance of mines, the assessment was narrowed down to focus on mines in the main producing countries as compiled by project-consult (Figure 8). This step already brings about a significant change in the frequency distributions (proportions of low, middle, and high EHP).

To illustrate this, Figure 9 shows, using gold as an example, each country's percentage share of the mines in the MRDS data (excluding USA, left-hand column) and each country's percentage share of global production (right-hand column). The figure shows that the order of the countries (by percentage share) is significantly different in the two columns. And a comparison of the two distributions of countries shows no statistical relationship between the number of mines and the volume of production.

Figure 9 Comparison of distribution of mines recorded in MRDS data by country with distribution of production by country, compiled by projekt-consult



Weighting of mine evaluation results according to main producing countries' shares of total production

In the third step, the results of the analysis of the MRDS data limited to the main producing countries are weighted according to countries' percentage shares of total production. This further increases the representative nature of the results in terms of importance (measured by volume of production). To start with, for the purpose of weighting, the sum of the known percentage shares of production by country (see Figure 6) was set at 100% for each of the five raw materials being studied (Table 9).

Table 9 Known percentage shares of production

Country	Gold	Copper	Bauxite	Graphite	Tungsten
Argentina		1 %			
Australia	12 %	6 %	34 %		
Bosnia Herzegovina			0.3 %		
Brazil	3 %	2 %	17 %	8 %	
Bulgaria		1 %			
Canada	5 %	4 %		3 %	1 %
Chile	2 %	39 %			
China	17 %	9 %	18 %	74 %	92 %
Ghana	4 %		0.2 %		
Greece			1 %		
Guinea			9 %		
Guyana			1 %		
India			6 %	15 %	
Indonesia	5 %	6 %			
Jamaica			5 %		
Kazakhstan	2 %		3 %		
Mexico	4 %				
Morocco		0.1 %			
Papua New Guinea	3 %				
Peru	8 %	9 %			
Poland		3 %			2 %
Portugal		1 %			
Russia	9 %	5 %	3 %		4 %
South Africa	9 %				
Surinam			2 %		
Sweden		1 %			
Turkey		1 %	0.4 %		
USA	12 %	8 %			
Uzbekistan	4 %				
Venezuela			1 %		
Zambia		5 %			
Total	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**

The results of the analysis of the MRDS data for producing countries are then weighted according to the countries' percentage shares of production, as follows. The sum of the weighted distribution figures of the producing countries is the overall weighted distribution:

weighted distribution = ∑ (country distribution x country's share of production)

These calculations are illustrated in Table 10 using gold and the "risk of naturally induced accidents" indicator as an example. The frequency distribution (low - medium - high) for each producing country, obtained through the analysis of the MRDS data collection, is multiplied by that country's percentage share of production and then the sum of all these products is calculated.

For example, the result of the evaluation of the MRDS data for gold mines in Australia shows the following frequency distribution for the "risk of naturally induced accidents" indicator:

53 % low – 34 % medium – 13 % high

Australia's percentage share of the total amount of gold produced by the main producing countries is 12% (Table 9). The weighted distribution for the "risk of naturally induced accidents" indicator is obtained by multiplying each country's distribution figures by the country's share of total production and calculating the sum of these figures for all the producing countries (Table 10).

Table 10 Outline of the process and results of the weighting of the "risk of naturally induced accidents" indicator for gold.

Country	Low	Medium	High
Weighting	Australia 53 %*12 % + Brazil 71 %*3 % + Chile 1 %*2 % + China 46 %*17 % + ….	Australia 34 %*12 % + Brazil 7 %*3 % + Chile 2 %*2 % + China 38 %*17 % + ….	Australia 13 %*12 % + Brazil 22 %*3 % + Chile 97 %*2 % + China 17 %*17 % + ….
Total	**40 %**	**33 %**	**28 %**

The number of cases (sites) is no longer relevant in this process, i.e. the weighting of country distribution figures. So statistical compensation for the high number of cases (mines) in the USA is not necessary.

5.3.6.3 Results of analysis and evaluation of data

The results of the process described here, of evaluation of natural environment indicators for the five raw materials, copper, gold, bauxite, graphite, and tungsten, are shown in the following illustrations.

It can be seen that the raw materials copper and gold in particular exhibit a relatively high percentage share for high hazard potential for the "risk of naturally induced accidents" and "water stress and arid areas" indicators. As a result of the envisaged increase in the extent of mines to 10 km, this percentage share may well increase further. In the case of graphite, there is a similar likelihood that there will be higher proportions of high hazard potentials for these two indicators.

In the case of copper, mines in Chile are very clearly the dominant influence on the results. For Chile, the evaluation of the MRDS data, which contained 357 cases (i.e. mines), showed that 98% of the mines are in areas with a high hazard potential as regards the "risk of naturally induced accidents" indicator. And where the "water stress and arid areas" indicator is concerned, it is as many as 99%. Added to this is the fact that Chile's share of the total production of the main producing countries is 39% (Table 9).

The situation is similar in the case of gold. But, unlike in the case of copper, Chile's share of the total production of the main producing countries is only 2%. The main gold producing countries are Australia, China, and the USA, whose shares of high hazard potential for the "water stress and arid areas" indicator lie between as much as 35% and 47%. Other major producing countries such as Russia (9%) and South Africa (9%) show very different results. In South Africa the proportion of mines with a high hazard potential for the "water stress and arid areas" indicator is 95% (231 mines in total), whereas in Russia the figure is 0% (162 mines in total).

The result for bauxite is determined primarily by conditions in Australia and secondly by those in China. Australia, with a share of total production (of the main producing countries) of 34%, is the largest producer of bauxite. China's share, as the second largest producer, is 18%. In the case of Australia, the evaluation of the MRDS data for the "risk of naturally induced accidents" indicator resulted in a 63% share of cases (mines) having a medium hazard potential.

The results for graphite are dominated by China (share of total production of main producing countries: 74%) in the case of the “risk of naturally induced accidents” indicator and by China and India (share of total production of main producing countries: 15%) in the case of the “water stress and arid areas” indicator. The evaluation of the MRDS data for India showed that 93% of cases (mines) have a high hazard potential for this indicator. There are 14 mines in each of the two countries.

China is also the main producer of tungsten (94% of total production of the main producing countries) and the results are correspondingly influenced by the evaluation of the MRDS data for China. The proportion of mines in China with a medium hazard potential for the “risk of naturally induced accidents” indicator is 73%, whereas the proportion of mines with a medium or high hazard potential for the “water stress and arid areas” and “protected areas” indicators is 0% in both cases. The MRDS data collection for China contains data on 30 mines.

Figure 10 Weighted distribution of the “natural environment” indicator for copper

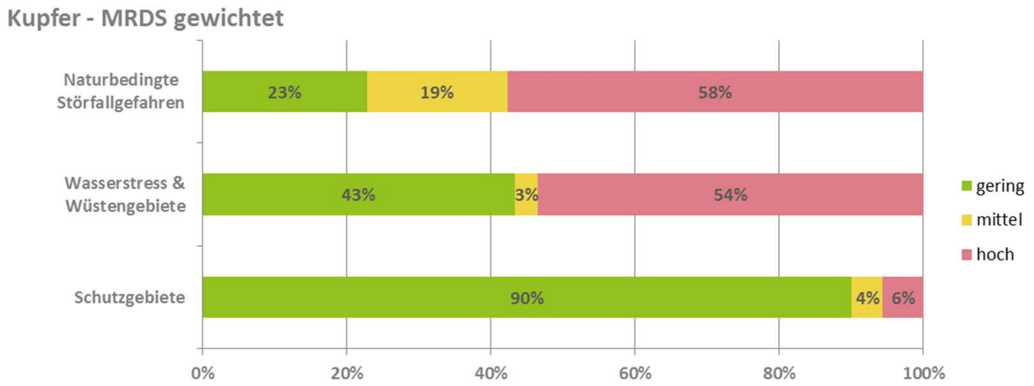


Figure 11 Weighted distribution of the “natural environment” indicator for gold

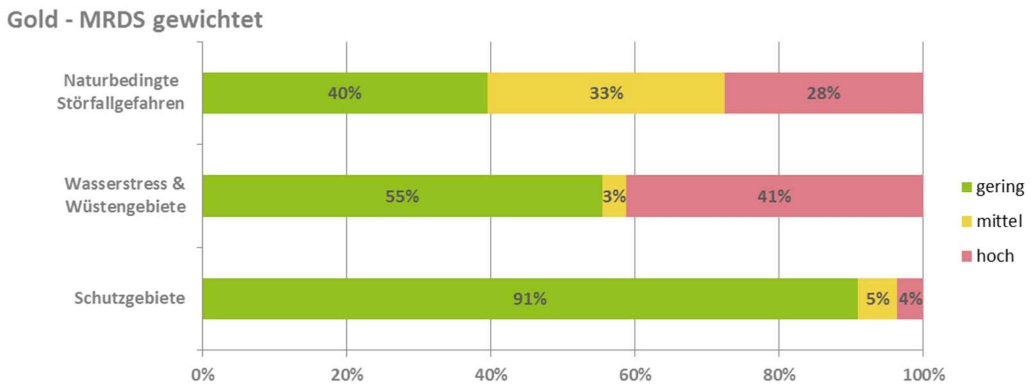


Figure 12 Weighted distribution of the “natural environment” indicator for bauxite

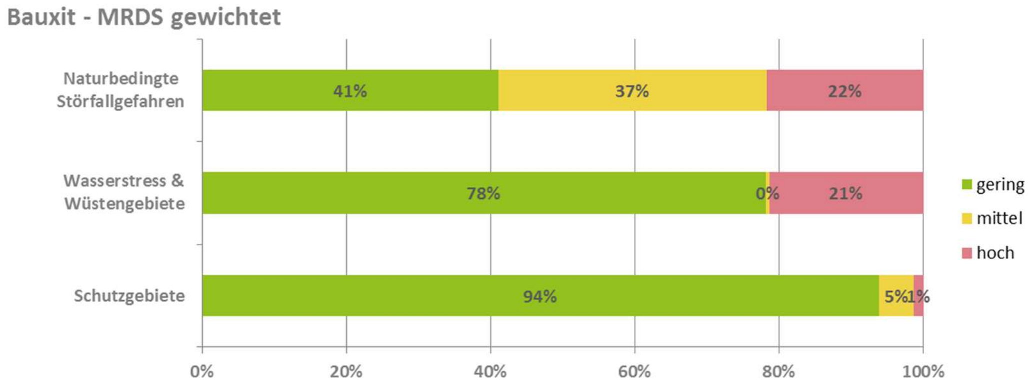


Figure 13 Weighted distribution of the “natural environment” indicator for graphite

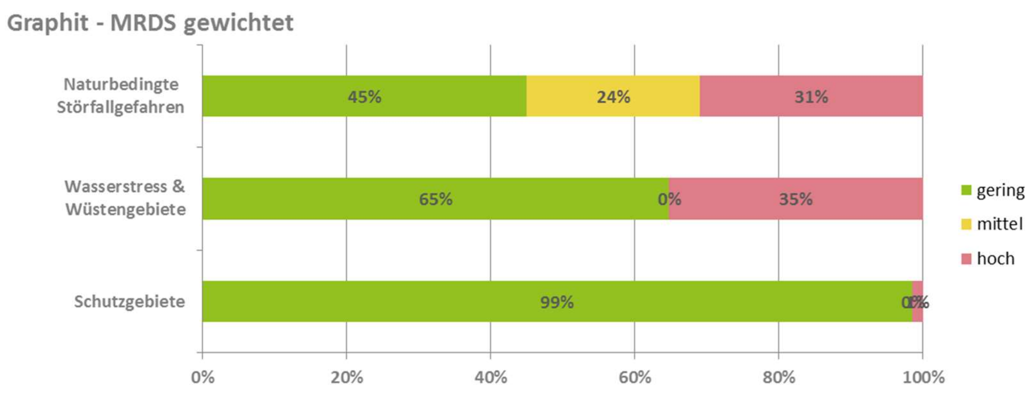
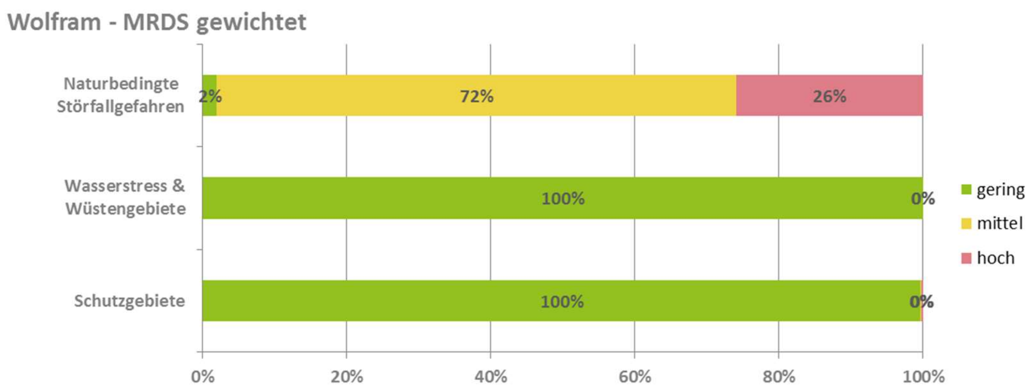


Figure 14 Weighted distribution of the “natural environment” indicator for tungsten



5.3.6.4 Outlook

During the OkoRess II project (FKZ 3715 32 310 0) significant individual cases (mines) will be examined in order to establish the extent to which further verification of the results of the evaluation using the method described here is both necessary and feasible. In principle, it would be possible to use the other georeferenced data collections of the USGS (section 5.3.6.1). Verification would also be possible by means of an examination of individual mines (e.g. tungsten mines in China, as far as possible, or evaluation of the top 10 or 20 mines, where data, e.g. for copper, is available (ICSG 2015)).

It only makes sense for the limits/boundaries for the raw material related assessment grid (Table 2) to be defined after the evaluation of the 51 raw materials, because only then will sufficient data have been collected for orientation on the basis of mathematical parameters such as mean, median, percentile, and variance.

5.4 Governance Level

5.4.1 Indicator 9: Environmental governance in the leading producing countries

As already explained in section 4.4, the authors recommend that indicators for the governance context be included as well as indicators for environmental factors. These (governance) indicators are used as a measure of risk enhancing or risk reducing factors. And they are supposed to indicate how likely it is that the environmental hazard potentials, which have been calculated using the other indicators, will actually manifest themselves in real environmental impacts. The approach described here has been drafted on the basis of initial reflections and has not been finalised as a proposed method. In-depth observation of governance issues and further development of relevant methods of assessment will be addressed in the ÖkoRess II project (FKZ 3715 32 310 0) and will be published in a subsequent publication.

In the meantime it is suggested that the World Bank's country governance indicators be used. This recommendation is based on the following logic:

As explained in section 4.2, the present assessment is based on an estimation of environmental hazard potentials, whereby, for practical reasons, site-specific measures taken to control the risks which these potentials represent, cannot be taken into account. Nevertheless, in order to estimate the extent to which effective environmental standards may be applied, the general assumption is made that effective environmental protection measures will be implemented especially in countries with good governance. It is of course possible for mining companies to implement high standards in regions with poor governance as well (on a voluntary basis, for example). But, as a rule, there are generally more opportunities to reduce costs by implementing standards only partially or not at all. This is made easier by the fact that in some jurisdictions either no standards or only poor standards are enforced, or they can be evaded with little cost or risk to the business.

For the approach chosen here, it is assumed that the degree of enforcement of standards depends primarily on the following factors:

1. Opportunities for participation in society, especially as regards being able to make successful complaints about abuses.
2. The extent to which standards and regulatory requirements can be undermined or ignored through corruption.

The Worldwide Governance Indicators (WGI) of the World Bank can be used to make an approximate assessment of these factors at the country level:

The World Bank publishes country data on six different aspects of governance at http://info.worldbank.org/governance/wgi/index.aspx#reports. The data is itself based on a wide range of other governance-based country rankings. The World Bank governance indicators are generally highly respected. The following indicators are available:

- Voice and Accountability
- Political Stability and Absence of Violence
- Government Effectiveness
- Regulatory Quality
- Rule of Law
- Control of Corruption

The indicator values in the original data set range from -2.5 (worst value) to 2.5 (best value). The countries are ranked in all six categories on the basis of this data. Depending on the position in the ranking, each country is awarded a percentage value (e.g. 100% for the first place, 0% for the last place).

The approach outlined here uses the country values for Voice and Accountability and Control of Corruption to make a rough assessment of the risk enhancing or risk reducing governance factors. This can serve as an indication of how high the risks are of inadequate involvement of local population groups and of standards not being met due to corruption. From the point of view of the authors, this has a significant influence on the probability of the environmental hazard potentials being managed by means of effective measures so that negative environmental impacts are avoided.

The assessment criteria set out in the table below are an initial draft and will be examined more rigorously and, if necessary, amended in the light of new findings, as part of the OkoRess II project (FKZ 3715323100).

Assessment

Low EHP:

In the three leading producing countries neither of the two indicators has a value of less than 50%.

Medium EHP:

In the three leading producing countries at least one indicator has a value of less than 50%, but neither indicator has a value of less than 25%.

High EHP:

In the three leading producing countries at least one of the two indicators has a value of less than 25%.

5.5 Value Chain Level

The raw material - commodity value chain is relevant to the evaluation of raw materials in two respects:

- The indicators in sections 5.1 to 5.3 specifically address the hazard potentials of the extraction and processing of raw materials. The further processing of raw materials (e.g. smelting, see Figure 2), which is usually carried out a long way from where the raw materials are extracted, is addressed only indirectly or not at all in the assessment[31].
- It is the global demand for raw materials which largely determines the magnitude and intensity of global primary production. The greater the global demand, the more numerous and/or larger mining projects tend to be. This then correlates with the overall environmental

[31] The indicators for geochemical composition of deposits sometimes provide information relevant to the pollution risks associated with smelting, for example. Emissions of sulphur compounds and heavy metals are, after all, a significant environmental problem at many smelting sites.

hazard potentials of the raw material[32], as the selected method of evaluation should show (see section 4.1).

It is therefore necessary to address these factors in a separate section of the raw material related assessment grid.

5.5.1 Indicator 10: Cumulative raw materials demand of global production ($CRMD_{global}$)

Mining always entails a direct interference in the natural world. The following effects (among others) are coupled with this:

- Use of land
- Degradation of soil and vegetation
- Interference with the local water balance
- Other environmental impacts resulting from the movement of earth and rock, spoil heaps, residues, etc.

However, there is no single indicator which can summarise these effects accurately. The cumulative raw materials demand (CRMD) is not sufficiently representative of environmental effects. And, on its own, it does not serve as a meaningful measure of potential environmental impact as a whole (see Müller et al, 2016a and Müller et al, 2016b).

Nevertheless, the cumulative raw materials demand is included as a scaling indicator of the order of magnitude of the global environmental hazard potentials calculated using all the other indicators[33]. It is defined as "the sum total of primary raw materials, including energy resources, which are used throughout the value chain in the manufacture and transportation of a product" (in this case a raw material/commodity). (VDI 2016) The indicator is therefore a measure of the total amount of: raw materials (ore) used throughout the value chain in the production of a standard commodity (e.g. refined copper)[34]; energy resources (especially fuels) required; and any other materials used in processing (e.g. chemicals) - everything measured in units of mass.

The cumulative raw materials demand of various commodities may be found in the VDI guideline VDI 4800 Part 2 (VDI 2016), in the publication by Giegrich et al (2012), and in ProBas (Umweltbundesamt 2017). It is important to note that in the case of raw materials obtained from ores containing more than one marketable raw material (e.g. copper ores containing by-products such as lead, zinc, silver, gold, and molybdenum), the calculation is based on an allocation process using economic criteria. This means that the masses (of raw materials) used in the extraction and processing of ores are allocated to the individual raw materials on a pro rata basis according to the respective shares of the total economic value. Table 11 gives an overview of the existing CRMD values presented in Giegrich et al (2012). In order to use the CRMD as an indicator in the evaluation method presented here, the CRMD value has to be multiplied by the annual global production of the raw material concerned. The result is an approximate estimation of the total mass of raw materials required for the global annual production of a raw material (see Table 11 and Figure 1).

[32] In the case of many abiotic raw materials, such as iron, aluminium, copper, and lead, a significant share of global demand is met from secondary sources (recycling). But this does nothing to change the fact that, due to growing demand, losses through dissipation, and thermodynamic limits, no commodity is obtained worldwide through recycling only.

[33] The higher the cumulative raw materials demand (as an indicator of the extent of worldwide activities for the production of a commodity), the higher are, e.g., the potential emissions of associated heavy metals or radioactive substances, the more auxiliary substances need to be used, and the more frequently the natural world is directly impacted by extraction itself.

[34] Including residues from processing, but not unused extracted material such as overburden and excavated soil. (For a definition of unused extracted material, see (Priester and Dolega 2015)).

Table 11 Annual primary production and cumulative raw materials demand (CRMD) for selected raw materials

Mineral	Annual production			Specific cumulative raw materials demand ($CRMD_{specific}$)	Cumulative raw materials demand of global production ($CRMD_{global}$)
	[t]	Reference Year	Source	[kg/t]	[t/yr]
Aluminium	58,300,000	2015	USGS 2016	10,412	607,019,600
Barite	7,460,000	2015	USGS 2016	9,105	67,923,300
Bauxite	274,000,000	2015	USGS 2016	1,141	367,434,000
Bentonite	16,000,000	2015	USGS 2016	1,008	16,128,000
Borate	5,860,000	2015	USGS 2016	2,885	16,906,100
Chromium	8,313,125	2015	Calculated using data from USGS 2016	21,956	182,522,973
Cobalt	124,000	2015	USGS 2016	56,884	7,053,616
Copper	18,700,000	2015	USGS 2016	128,085	2,395,189,500
Diatomite	2,290,000	2015	USGS 2016	2,286	5,234,940
Fluorspar	6,250,000	2015	USGS 2016[35]	1,179	7,368,750
Gallium	74	2014	Reichl et al, 2016	1,666,985	123,357
Gold	3,000	2015	USGS 2016	740,317,694	2,220,953,082
Graphite	1,190,000	2015	USGS 2016	1,066	1,268,540
Gypsum	258,000,000	2015	USGS 2016	1,011	260,838,000
Indium	755	2015	USGS 2016	25,753,922	19,444,211
Iron	1,180,000,000	2015	USGS 2016[36]	4,126	4,868,680,000
Kaolin	34,000,000	2015	USGS 2016	4,736	161,024,000
Limestone	350,000,000	2015	USGS 2016	1,001	350,350,000
Lithium	32,500	2015	USGS 2016	13,265	431,113

[35] Data excluding USA.

[36] Data for pig iron.

Mineral	Annual production			Specific cumulative raw materials demand ($CRMD_{specific}$)	Cumulative raw materials demand of global production ($CRMD_{global}$)
	[t]	Reference Year	Source	[kg/t]	[t/yr]
Magnesite	8,300,000	2015	USGS 2016	2,106	17,479,800
Magnesium	910,000	2015	USGS 2016	5,051	4,596,410
Manganese	18,000,000	2015	USGS 2016	8,224	148,032,000
Molybdenum	267,000	2015	USGS 2016	989,114	264,093,438
Nickel	2,530,000	2015	USGS 2016	133,105	336,755,650
Palladium	208	2015	USGS 2016	36,937,268[37]	7,682,952
Perlite	2,680,000	2015	USGS 2016	1,457	3,904,760
Phosphate	223,000,000	2015	USGS 2016	18,308[38]	4,082,684,000
Platinum	178	2015	USGS 2016	128,778,574[39]	22,922,586
Potassium salt	38,800,000	2015	USGS 2016[40]	7,736	300,156,800
Quartz sand	181,000,000	2015	USGS 2016	1,088	196,928,000
Selenium	2,797	2014	BGS 2016	3,810	10,657
Silicon	8,100,000	2015	USGS 2016	37,771	305,945,100
Silver	27,300	2015	USGS 2016	6,834,797	186,589,958
Talc	7,320,000	2015	USGS 2016	1,407	10,299,240
Tantalum	1,200	2015	USGS 2016	9,179,654	11,015,585
Tin	294,000	2015	USGS 2016	1,178,827	346,575,138
Titanium	4,015,638	2014	Calculated using data from BGS 2016	39,522	158,705,045
Tungsten	87,000	2015	USGS 2016	343,423	29,877,801

37 Average of data from Russia (22,435,523 kg/t) and South Africa (51,439,013 kg/t)

38 Average of data from Morocco (8,221 kg/t) and USA (28,395 kg/t)

39 Average of data from Russia (67,503,863 kg/t) and South Africa (190,053,285 kg/t)

40 Figures are K_2O-equivalent

Mineral	Annual production			Specific cumulative raw materials demand ($CRMD_{specific}$)	Cumulative raw materials demand of global production ($CRMD_{global}$)
	[t]	Reference Year	Source	[kg/t]	[t/yr]
Zinc	13,400,000	2015	USGS 2016	13,554	181,623,600

Sources: British Geological Survey 2016; Giegrich et al, 2012; Reichl et al, 2016; U.S. Geological Survey 2016

An alternative approach would be to estimate the mass of material (excluding the mass of the fuels and auxiliary chemicals used in processing) required to produce a raw material. Data subsets from Giegrich et al (2012) (CRMD metal ores + CRMD rocks and earth) could be used in this case.

Alternatively, it is possible to make credible estimates of the masses of raw materials used annually using data on the typical concentration of ore deposits and the annual global production of a raw material. This involves the following calculation:

TM = MP/C x 100

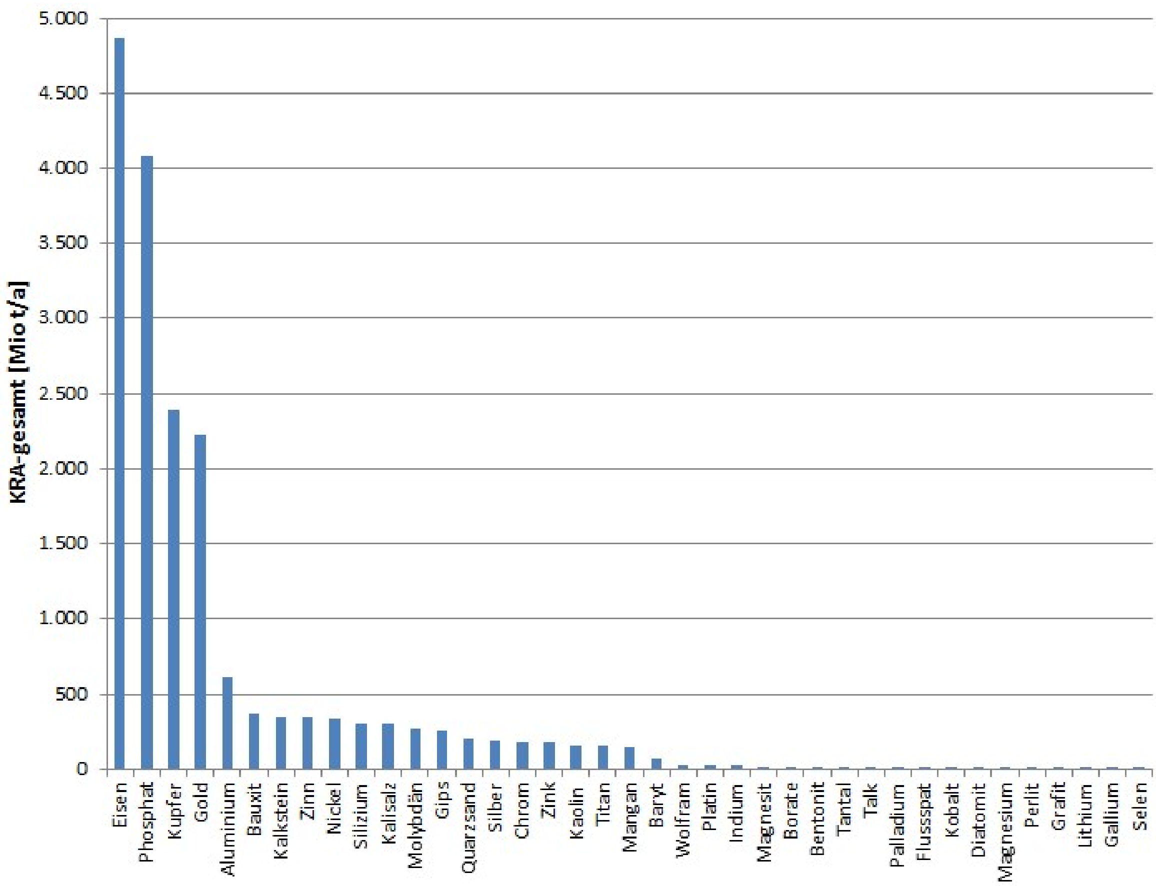
TM = total mass required to produce the raw material (excluding auxiliary substances used in processing) [t/yr]

MP = annual global production of the primary raw material [t/yr]

C = typical concentration of the raw material in ore deposits [%]

In order to avoid double counting when estimating the total mass of material extracted, the proportion of by-products (companionality) needs to be accounted for by applying appropriate rules for allocation. Nassar et al (2015) determined this proportion for 62 raw materials.

Figure 15 Graph showing the cumulative raw materials demand of global production of selected raw materials using the figures presented in Table 11



The threshold values set out below were derived from an evaluation of the data in Table 11, whereby the 39 raw materials under consideration were distributed equally into the three classes of environmental hazard potential (13 per class). This distribution was used to determine the threshold values listed below. If the evaluation is extended to other raw materials or if the method of evaluation is modified significantly, an adjustment of the threshold limits of the classes may be necessary.

Assessment

Low EHP:

$CRMD_{global}$ < 16.5 million t/yr

Medium EHP:

$CRMD_{global}$ between 16.5 and 200 million t/yr

High EHP:

$CRMD_{global}$ > 200 million t/yr

It should be noted that all the approaches selected here have weaknesses, which can be summarised as follows:

- The method which makes use of the CRMD takes into account not only the mass of material extracted but also the mass of auxiliary materials and fuels. As a result, this overlaps to some extent with indicator 11 (cumulative energy demand of global production of raw materials, CED_{global}).
- In the mining industry, only the mass of mined material ("run-of-mine") is taken into account. This only includes material which is directly associated with the ore or raw material being extracted. Other masses of material which may be moved, such as surface layers of rock and overburden, are not included in the calculation.
- The global annual production of raw materials is subject to fluctuation. This is not shown in Table 11. And as deposits become increasingly depleted there may be a long-term reduction in the mineral content of ores. This trend is well documented in the case of copper, for example, although rapid or sudden decreases in concentration are not expected during the next ten years (Northey et al 2014).
- The quantifiable environmental impacts do not correlate very closely with the cumulative raw materials demand (Giegrich et al 2012; Müller et al 2016). Attention needs to be given to other influential factors, such as primary energy consumption, the method of extraction, the geochemical composition of mining waste, and the vulnerability of the affected ecosystems. These influential factors are accounted for by a number of other indicators, however[41].

5.5.2 Indicator 11: Total primary energy used in global raw material production

The cumulative energy demand is included as an additional scaling indicator of the order of magnitude of the global environmental hazard potentials calculated using all the other indicators. This indicator is based on the most robust LCI data on the primary energy demand of the production of individual raw materials (see section 3.2) and reflects the total primary energy used annually in the global production of a raw material.

[41] No. 11 for primary energy consumption, nos. 4 and 5 for the type of mining, nos. 1-3 for the geochemical composition of ores and, together with No. 5, also for the composition of residues, nos. 7 and 8 for the vulnerability of affected ecosystems.

As regards data, it is possible to make use of databanks concerned with ecological balance, such as ProBas[42] and EcoInvent[43], although these figures need to be multiplied by the data on global primary production (see Table 12).

[42] http://www.probas.umweltbundesamt.de/php/index.php

[43] http://www.ecoinvent.org/

Table 12 Cumulative energy demand (CED) of 1 t of raw material and of annual global production (CEDglobal)

Mineral	Specific cumulative energy demand (CED) [MJ/t]	Source	Annual production[44] [t/yr]	Primary energy demand of one year's production (CED_{global}) [TJ/yr]
Aluminium	131,000	Nuss und Eckelman (2014)	58,300,000	7,637,300
Antimony	141,000	Nuss und Eckelman (2014)	150,000	21,150
Barite	14,996	ProBas[45]	7,460,000	111,870
Bauxite	109	ProBas[46]	274,000,000	29,866
Bentonite	354	ProBas[47]	16,000,000	5,664
Beryllium	1,720,000	Nuss und Eckelman (2014)	300	516
Borate	26,035	ProBas[48]	5,860,000	152,565
Chromium	484,371	Nuss und Eckelman (2014)	8,313,125	334,188
Cobalt	128,000	Nuss und Eckelman (2014)	124,000	15,872
Copper	50,700	Nuss und Eckelman (2014)	18,700,000	1,004,190
Diatomite	6,214	IFEU 2012[49]	2,290,000	14,230
Fluorspar	1,356	ProBas[50]	6,250,000	8,475
Gallium	3,030,000	Nuss und Eckelman (2014)	74	224
Germanium	2,890,000	Nuss und Eckelman (2014)	165	477
Gold	208,000,000	Nuss und Eckelman (2014)	3,000	624,000
Graphite	437	ProBas[51]	1,190,000	520
Gypsum	29	ProBas[52]	258,000,000	7,379
Indium	1,720,000	Nuss und Eckelman (2014)	755	1,299
Iron	23,100	Nuss und Eckelman (2014)	1,180,000,000	27,258,000
Kaolin & kaolinite	3,282	ProBas[53]	34,000,000	111,588
Limestone	24	ProBas[54]	350,000,000	8,540
Lithium	125,000	Nuss und Eckelman (2014)	32,500	4,063
Magnesium	18,800	Nuss und Eckelman (2014)	910,000	17,108
Manganese	23,700	Nuss und Eckelman (2014)	18,000,000	426,600
Molybdenum	117,000	Nuss und Eckelman (2014)	267,000	31,239
Nickel	111,000	Nuss und Eckelman (2014)	2,530,000	280,830
Niobium	172,000	Nuss und Eckelman (2014)	56,000	9,632
Palladium	72,700,000	Nuss und Eckelman (2014)	208	15,122
Perlite	14,169	ProBas[55]	2,680,000	37,973
Platinum	243,000,000	Nuss und Eckelman (2014)	178	43,254
Potassium carbonate	5,345	ProBas[56]	38,800,000	207,386
Quartz sand	287	ProBas[57]	181,000,000	51,947
Rhenium	9,040,000	Nuss und Eckelman (2014)	46	416

[44] For sources and years to which data apply, see Table 11.

[45] Geographical coverage (Weltmix); Time frame (2004)

Rock phosphate	3,962	ProBas[58]	223,000,000	883,526
Selenium	65,500	Nuss und Eckelman (2014)	2,797	183
Silicon	1,416,614	ProBas[59]	8,100,000	11,474,573
Silver	3,280,000	Nuss und Eckelman (2014)	27,300	89,544
Talc	434	ProBas[60]	7,320,000	3,177
Tantalum	4,360,000	Nuss und Eckelman (2014)	1,200	5,232
Tin	321,000	Nuss und Eckelman (2014)	294,000	94,374
Titanium	115,000	Nuss und Eckelman (2014)	4,015,638	461,798
Tungsten	133,000	Nuss und Eckelman (2014)	87,000	11,571
Vanadium	516,000	Nuss und Eckelman (2014)	79,400	40,970
Zinc	52,000	Nuss und Eckelman (2014)	13,400,000	696,800

A summary of this data for 44 raw materials is presented in Figure 16.

46 Geographical coverage (Germany); Time frame (1994 -2004)

47 Geographical coverage (Weltmix); Time frame (2004)

48 Geographical coverage (Weltmix); Time frame (2000 -2004)

49 Geographical coverage (Weltmix); Time frame (2004)

50 Geographical coverage (Weltmix); Time frame (2000 -2004)

51 Geographical coverage (Europe); Time frame (2000 -2004)

52 Geographical coverage (Germany); Time frame (2000 -2004)

53 Geographical coverage (Europe); Time frame (2004)

54 Geographical coverage (Germany); Time frame (2000 -2004)

55 Geographical coverage (Germany); Time frame (1995 -2004)

56 Geographical coverage (Europe); Time frame (2000 -2004)

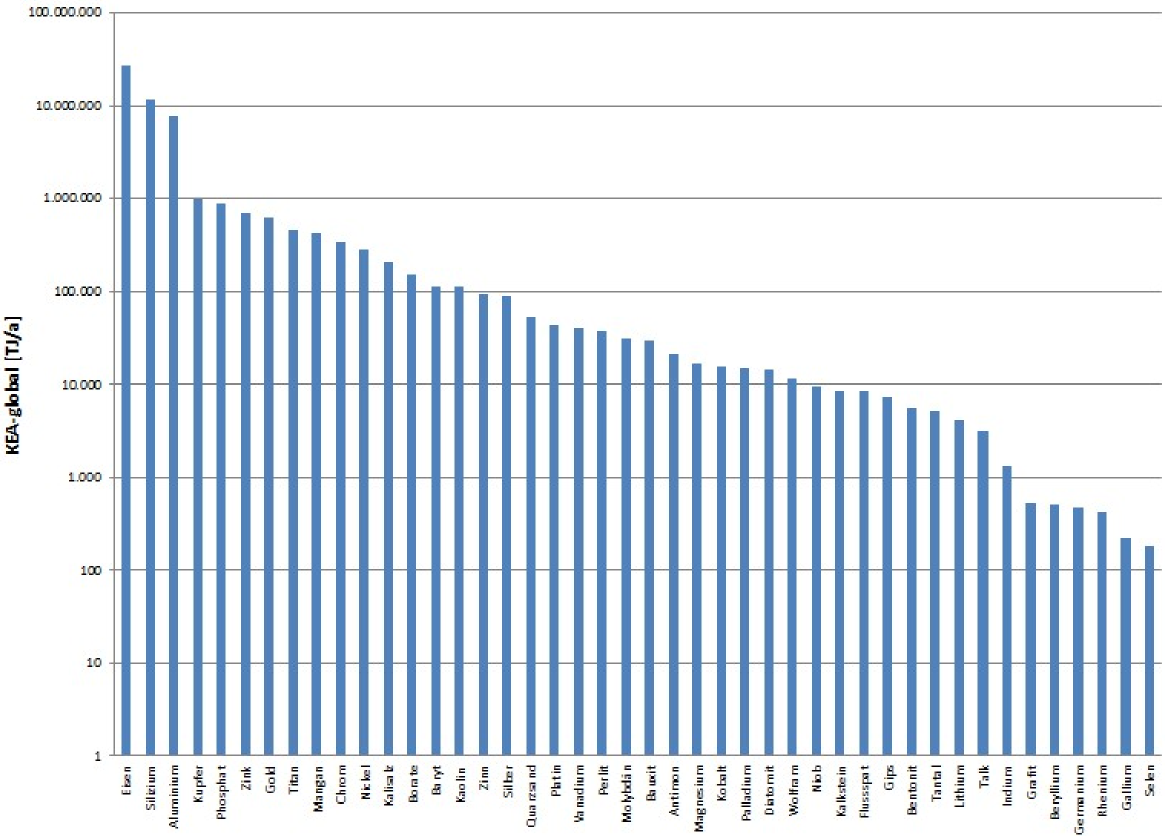
57 Geographical coverage (Germany); Time frame (2000 -2004)

58 Geographical coverage (USA); Time frame (1986 -2004)

59 Geographical coverage (Germany); Time frame (2000 -2005)

60 Geographical coverage (Weltmix); Time frame (2000 -2004)

Figure 16 Total primary energy use for the annual production of selected abiotic raw materials (Y-axis is a logarithmic scale.)



The data in Table 12 was used to calculate the threshold values listed in the table below. The 44 raw materials were distributed equally as far as possible between the three classes. With 15 raw materials allocated to each of the high and low classes of environmental hazard potential and 14 allocated to the medium EHP class, the resulting threshold values are shown below. If the evaluation is extended to other raw materials, an adjustment of the threshold limits of the classes may be necessary.

Assessment

Low EHP:

$CRMD_{global} < 10{,}000$ TJ/yr

Medium EHP:

$CRMD_{global}$ between 10,000 and 100,000 TJ/yr

High EHP:

$CRMD_{global} > 100{,}000$ TJ/yr

6 Evaluation of data quality

When using the assessment grid described in chapters 4 and 5, it is necessary to assume that, in spite of all the guidance and the sources of data which are quoted, there are likely to be gaps and/or evaluations based on data which is not entirely representative. It is therefore recommended that details of the quality of the underlying data be attached to the evaluation of individual indicators. The following quality classes are recommended:

Evaluation of data quality

High:

The evaluation is based on scientifically obtained data. The data are by and large representative of the global production of the raw material subject to evaluation.

Medium:

The evaluation is based on scientific estimates and deduction. This includes both expert knowledge and credible extrapolation from a limited number of site observations. The evaluation is nevertheless rated as entirely accurate, so it is most unlikely that any collection of additional data would necessitate a revision of the evaluation.

Low:

The evaluation is based on scientific estimates and deduction. This includes both expert knowledge and credible extrapolation from a limited number of site observations. The evaluation is rated as entirely accurate, but one cannot rule out the possibility that a collection of additional data might necessitate a revision of the evaluation.

7 Application of the method of evaluation to selected raw materials

In the case of some indicators, the application of the method of evaluation is provisional and will only be completed as part of ÖkoRess II. This applies especially to indicators 6-8. At this point in time threshold limits for these indicators have been derived only for five raw materials which were investigated as examples. For the purposes of simplification these threshold values were derived on the basis of the means of the frequency distributions of the three indicators (see section 5.3.6.3). Final specification of the threshold limits requires a larger statistical analysis which will be conducted as part of ÖkoRess II. A broader collection of data for all raw materials will be used in ÖkoRess II, so it will be possible to make a proposal as regards definition of the threshold limits for low, medium, and high EHP.

7.1 Copper

Rating	Rationale	Data quality
Indicator 1: Preconditions for Acid Mine Drainage (AMD)		
High EHP	According to the Goldschmidt classification, copper is one of the chalcophile (sulphur-loving) elements and occurs mostly in the form of sulphides (see section 5.1.1).	High
Indicator 2: Associated heavy metals		
High EHP	Copper is an element which itself has toxic qualities. And it is defined as a heavy metal for the purposes of this method description (see section 5.1.2).	High
Indicator 3: Associated radioactive substances		
Medium EHP	There is no systematic data on the association of Cu with U and Th in commercially viable deposits. Data from Chinese Cu deposits show low concentrations of U and Th (see section 5.1.3). However, the Chinese deposits are an insufficient basis for evaluation, because they account for only a limited share of the world market. Due to the gaps in the data, a medium EHP rating is given in accordance with the recommendation in section 5.1.3.	Low
Indicator 4: Method of extraction		
Medium EHP	Most copper is produced through opencast mining of massive ores, such as those in the subduction zones around the "Ring of Fire" (copper porphyry). Opencast mining of solid rock is assigned a medium EHP (see section 5.2.1).	High
Indicator 5: Use of auxiliary chemicals		
High EHP	The standard method of processing is flotation with solvent extraction (sulphuric acid). The use of toxic auxiliary substances is assigned a high EHP (see section 5.2.2).	Medium

Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides		
High EHP	The weighted distribution for a high hazard potential is 58% (see section 5.3.6.3). This lies above the mean for the five raw materials (33%).	Low
Indicator 7: Water stress index and arid regions		
High EHP	The weighted distribution for a high hazard potential is 54% (see section 5.3.6.3). This lies above the mean for the five raw materials (30%).	Low
Indicator 8: Designated protected areas and AZE sites		
High EHP	The weighted distribution for a high hazard potential is 6% (see section 5.3.6.3). This lies above the mean for the five raw materials (2%).	Low
Indicator 9: Environmental governance in the leading producing countries		
High EHP	The three largest copper producing countries are Chile, China, and Peru with global market shares of 31.1%, 9.5%, and 7.5% (USGS 2016). According to data from 2014, the values of the WGI indicator Voice & Accountability for the three countries are 80.30%, 5.42% and 51.23%. The data on Control of Corruption exhibit values of 90.87%, 47.12% and 32.69%. There is therefore one indicator value below 25% (Voice & Accountability for China) (World Bank 2016).	High
Indicator 10: Cumulative raw materials demand of global production		
High EHP	The cumulative raw materials demand of copper is 128,085 kg/t, according to Giegrich et al (2012). With annual primary production of 18,700,000 tonnes in 2015 (USGS 2016), the total (global) cumulative raw materials demand is almost 2.4 billion t (see section 5.5.1). This is far above the threshold limit for high EHP ($CRMD_{global}$ > 200 million t/yr).	High
Indicator 11: Cumulative energy demand of global raw material production		
High EHP	According to Nuss, Eckelmann (2014), the cumulative energy demand of copper is 50,700 MJ/t. With annual primary production of 18,700,000 tonnes in 2015 (USGS 2016), the total (global) cumulative energy demand is just over 1 million TJ/yr (see section 5.5.2). This exceeds the threshold limit for high EHP (CED_{global} > 100,000 TJ/a) by a factor of ten.	High

Additional information:
1. The ratings for indicators 6-8 are provisional. They serve only as an illustration and a basis for further discussion of the aggregation of the results. 2. The methodological approach for indicator 9 is to be regarded as provisional. It will be examined in depth and possibly modified as part of the ÖkoRess II project (FKZ 3715 32 310 0).
References:
Giegrich et al, 2012: Indikatoren/Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion. UBA-Texte 01/2012, Dessau, 2012. Nuss, Eckelmann, 2014: Life Cycle Assessment of Metals: A Scientific Synthesis. In: PLoS ONE 9 (7), 2014. USGS, 2016: Mineral Commodity Summaries 2016. Reston, 2016. The World Bank, 2016: Worldwide Governance Indicators. Internet: http://info.worldbank.org/governance/wgi/#home

7.2 Gold

Rating	Rationale	Data quality
Indicator 1: Preconditions for Acid Mine Drainage (AMD)		
Medium EHP	According to the Goldschmidt classification, gold is a siderophile element (iron-loving). Nevertheless it occurs not only as sulphides, but also in the form of pure oxides (see section 5.1.1).	Medium
Indicator 2: Associated heavy metals		
Medium EHP	Gold is a precious metal and is not toxic. However, in deposits it is often associated with heavy metals (e.g. in Cu-Au ores) (see section 5.1.2).	Medium
Indicator 3: Associated radioactive substances		
High EHP	Gold from deep underground mines in South Africa (approximately 7.5% of world production) is associated with high concentrations (0.02%) of uranium (Lloyd 1981, Durand 2012).	Low
Indicator 4: Method of extraction		
Medium EHP	Gold is usually extracted through opencast mining of massive ore deposits (stockworks, porphyry). Opencast mining of solid rock is assigned a medium EHP (see section 5.1.1).	High

Indicator 5: Use of auxiliary chemicals		
High EHP	In large industrial mines gold is extracted by leaching with cyanide; in small mines usually by amalgamation (using mercury). The use of toxic auxiliary substances is assigned a high EHP (see section 5.2.2).	High
Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 7: Water stress index and arid regions		
High EHP	The weighted distribution for a high hazard potential is 41% (see section 5.3.6.3). This lies above the mean for the five raw materials (30%).	Low
Indicator 8: Designated protected areas and AZE sites		
High EHP	The weighted distribution for a high hazard potential is 4% (see section 5.3.6.3). This lies above the mean for the five raw materials (2%).	Low
Indicator 9: Environmental governance in the leading producing countries		
High EHP	The three largest gold producing countries are China, Australia, and Russia with global market shares of 15.1%, 9.2%, and 8.3% (USGS 2016). According to data from 2014, the values of the WGI indicator Voice & Accountability for the three countries are 5.42%, 93.6% and 20.2%. The data on Control of Corruption exhibit values of 47,12 %, 95,19 % and 19,71 %. Thus, a total of three indicator values lie below 25% (Control of Corruption for China and Voice & Accountability for both China and Russia).	High
Indicator 10: Cumulative raw materials demand of global production		
High EHP	The cumulative raw materials demand of gold is 740,317,694 kg/t, according to Giegrich et al (2012). With annual production of 3,000 t in 2015 (USGS 2016), the total cumulative raw materials demand is approximately 2.4 billion t (see section 5.5.1).	High

Indicator 11: Cumulative energy demand of global raw material production		
High EHP	According to Nuss, Eckelmann (2014), the cumulative energy demand of gold is 208,000,000 MJ/t. With annual production of 3,000 t in 2015 (USGS 2016), the total cumulative energy demand is approximately 624,000 TJ/yr (see section 5.5.2).	High
Additional information:		
1. The ratings for indicators 6-8 are provisional and serve only as an illustration and a basis for further discussion of the aggregation of the results. 2. The methodological approach for indicator 9 is to be regarded as provisional. It will be examined in depth and possibly modified as part of the ÖkoRess II project (FKZ 3715323100).		
References:		
Giegrich et al, 2012: Indikatoren/Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion. UBA-Texte 01/2012, Dessau, 2012. Durand, J.F., 2012: The impact of gold mining on the Witwatersrand on the rivers and karst systems of Gauteng and North West Province, South Africa. In: Journal of African Earth Science, 68, pp. 24-43, 2012. Nuss, Eckelmann, 2014: Life Cycle Assessment of Metals: A Scientific Synthesis. In: PLoS ONE 9 (7), 2014. USGS, 2016: Mineral Commodity Summaries 2016. Reston, 2016. The World Bank, 2016: Worldwide Governance Indicators. Internet: http://info.worldbank.org/governance/wgi/#home		

7.3 Aluminium

Rating	Rationale	Data quality
Indicator 1: Preconditions for Acid Mine Drainage (AMD)		
Low EHP	According to the Goldschmidt classification, aluminium is a lithophile element. It occurs mostly in the form of oxides (see section 4.1.1).	High
Indicator 2: Associated heavy metals		
Medium EHP	Aluminium is not a heavy metal. A medium EHP rating is assigned in accordance the recommendations regarding metals in section 5.1.2.	Medium

Indicator 3: Associated radioactive substances		
Medium EHP	Data on Chinese bauxite deposits (16.3% of world production) indicate that, on average, aluminium is often associated with slightly elevated concentrations of uranium and/or thorium (see section 5.1.3).	Medium
Indicator 4: Method of extraction		
High EHP	Bauxite is extracted from lateritic strata in the tropics, which are close to the surface and therefore lend themselves to opencast mining (of loose rock) as the method of extraction.	High
Indicator 5: Use of auxiliary chemicals		
High EHP	Processing: digestion using caustic soda in the Bayer process.	High
Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides		
Medium EHP	The weighted distribution for a medium hazard potential is 37.2% (see section 5.3.6.3). This lies just above the mean for the five raw materials (37.1%).	Low
Indicator 7: Water stress index and arid regions		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 8: Designated protected areas and AZE sites		
Medium EHP	The weighted distribution for a medium hazard potential is 5% (see section 5.3.6.3). This lies above the mean for the five raw materials (3%).	Low
Indicator 9: Environmental governance in the leading producing countries		
High EHP	The three leading Bauxite producing countries are Australia, China, and Brazil with global market shares of 32.1%, 22.4%, and 14.2% (USGS 2016). According to data from 2014, the values of the WGI indicator Voice & Accountability for the three countries are 93.60%, 5.42% and 60.59%. The data on Control of Corruption exhibit values of 95,19 %, 47,12% and 44,23 %. There is therefore one indicator value below 25% (Voice & Accountability for China).	High

Indicator 10: Cumulative raw materials demand of global production		
High EHP	The cumulative raw materials demand of aluminium is 10,412 kg/t, according to Giegrich et al, 2012. With annual production of 58,300,000 t in 2015 (USGS 2016), the total cumulative raw materials demand is approximately 607 billion t (see section 5.5.1).	High
Indicator 11: Cumulative energy demand of global raw material production		
High EHP	According to Nuss, Eckelmann (2014), the cumulative energy demand of aluminium is 131,000 MJ/t. With annual production of 58,300,000 t in 2015 (USGS 2016), the total cumulative energy demand is approximately 7.6 TJ/yr (see section 5.5.2).	High
Additional information:		
1. The ratings for indicators 6-8 are provisional. They serve only as an illustration and a basis for further discussion of the aggregation of the results. 2. The methodological approach for indicator 9 is to be regarded as provisional. It will be examined in depth and possibly modified as part of the ÖkoRess II project (FKZ 3715323100).		
References:		
Giegrich et al, 2012: Indikatoren/Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion. UBA-Texte 01/2012, Dessau, 2012. Nuss, Eckelmann, 2014: Life Cycle Assessment of Metals: A Scientific Synthesis. In: PLoS ONE 9 (7), 2014. USGS, 2016: Mineral Commodity Summaries 2016. Reston, 2016. The World Bank, 2016: Worldwide Governance Indicators. Internet: http://info.worldbank.org/governance/wgi/#home		

7.4 Tungsten

Rating	Rationale	Data quality
Indicator 1: Preconditions for Acid Mine Drainage (AMD)		
Medium EHP	According to the Goldschmidt classification, tungsten is a siderophile element (iron-loving). It occurs both as sulphides and as oxides (see section 5.1.1).	Medium
Indicator 2: Associated heavy metals		
Medium EHP	Tungsten is not classed as a toxic heavy metal. A medium EHP rating is assigned in accordance with the recommendations regarding metals in section 5.1.2.	Medium

Indicator 3: Associated radioactive substances		
Medium EHP	No specific data is available. A medium EHP rating is assigned as a result of following the process described in section 5.1.3.	Low
Indicator 4: Method of extraction		
Low EHP	Tungsten is extracted as wolframite or scheelite in underground mines, because the deposits are usually veins or metasomatic deposits, which are small-scale and require selective extraction.	Medium
Indicator 5: Use of auxiliary chemicals		
Medium EHP	Tungsten ores are processed using gravity concentration and sink-float separation. Tungsten may occasionally be refined through indirect flotation (flotation of the associated minerals which are contaminants).	Medium
Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides		
Medium EHP	The weighted distribution for a medium hazard potential is 72% (see section 5.3.6.3). This lies above the mean for the five raw materials (37%).	Low
Indicator 7: Water stress index and arid regions		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 8: Designated protected areas and AZE sites		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 9: Environmental governance in the leading producing countries		
High EHP	The three leading tungsten producing countries are China, Vietnam, and Portugal with global market shares of 81.8%, 4.6%, and 3.2% (USGS 2016). According to data from 2014, the values of the WGI indicator Voice & Accountability for the three countries are 5.42%, 9.85% and 83.25%. The data on Control of Corruption exhibit values of 47.12%, 37.5% and 79.33%. There are therefore two indicator values below 25% (Voice & Accountability for both China and Vietnam).	High

Indicator 10: Cumulative raw materials demand of global production		
Medium EHP	The cumulative raw materials demand of tungsten is 343,423 kg/t, according to Giegrich et al, 2012. With annual production of 87,000 t in 2015 (USGS 2016), the total cumulative raw materials demand is almost 30 billion t (see section 5.5.1).	High
Indicator 11: Cumulative energy demand of global raw material production		
Medium EHP	According to Nuss, Eckelmann (2014), the cumulative energy demand of tungsten is 133,000 MJ/t. With annual production of 87,000 t in 2015 (USGS 2016), the total cumulative energy demand is 11,571 TJ/yr (see section 5.5.2).	High
Additional information:		
1. The ratings for indicators 6-8 are provisional. They serve only as an illustration and a basis for further discussion of the aggregation of the results. 2. The methodological approach for indicator 9 is to be regarded as provisional. It will be examined in depth and possibly modified as part of the ÖkoRess II project (FKZ 3715323100).		
References:		
Giegrich et al, 2012: Indikatoren/Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion. UBA-Texte 01/2012, Dessau, 2012. Nuss, Eckelmann, 2014: Life Cycle Assessment of Metals: A Scientific Synthesis. In: PLoS ONE 9 (7), 2014. USGS, 2016: Mineral Commodity Summaries 2016. Reston, 2016. The World Bank, 2016: Worldwide Governance Indicators. Internet: http://info.worldbank.org/governance/wgi/#home		

7.5 Graphite

Rating	Rationale	Data quality
Indicator 1: Preconditions for Acid Mine Drainage (AMD)		
Low EHP	Graphite does not normally occur as a sulphide.	Medium
Indicator 2: Associated heavy metals		
Low EHP	Graphite is an abiotic non-metallic raw material. A value of 0 has been assigned in accordance with the recommendations in section 4.1.2. If evidence is found of association with heavy metals, the evaluation will have to be adjusted accordingly.	Low
Indicator 3: Associated radioactive substances		

Low EHP	Graphite does not occur in association with radioactive substances.	Medium
Indicator 4: Method of extraction		
Low EHP	Graphite is usually extracted from underground mines, because the deposits are usually veins which require selective extraction.	Medium
Indicator 5: Use of auxiliary chemicals		
Medium EHP	Graphite is usually processed by flotation with the aid of auxiliary chemicals	Medium
Indicator 6: Risk of accident due to flooding, earthquakes, storms, and landslides		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 7: Water stress index and arid regions		
High EHP	The weighted distribution for a high hazard potential is 35% (see section 5.3.6.3). This lies above the mean for the five raw materials (30%).	Low
Indicator 8: Designated protected areas and AZE sites		
Low EHP	The weighted distributions for a medium and for a high risk potential are below the mean for the five raw materials.	Low
Indicator 9: Environmental governance in the leading producing countries		
High EHP	The three leading graphite producing countries are China, India, and Brazil with global market shares of 65.6%, 14.3%, and 6.7% (USGS 2016). According to data from 2014, the values of the WGI indicator Voice & Accountability for the three countries are 5.42%, 61.08% and 60.59%. The data on Control of Corruption exhibit values of 47.12%, 38.94%, and 44.23 %. There is therefore one indicator value below 25% (Voice & Accountability for China).	High
Indicator 10: Cumulative raw materials demand of global production		
Low EHP	The cumulative raw materials demand of graphite is 1,066 kg/t, according to Giegrich et al, 2012. With annual production of 1,190,000 t in 2015 (USGS 2016), the total cumulative raw materials demand is approximately 1.2 million t (see section 5.5.1).	High
Indicator 11: Cumulative energy demand of global raw material production		

Low EHP	According to ProBas data (see Giegrich et al, 2012), the cumulative primary energy demand of graphite is 437 MJ/t. With annual production of 1,190,000 t in 2015 (USGS 2016), the total cumulative energy demand is 520 TJ/yr (see section 5.5.2).	High

Additional information:

1. The ratings for indicators 6-8 are provisional. They serve only as an illustration and a basis for further discussion of the aggregation of the results.
2. The methodological approach for indicator 9 is to be regarded as provisional. It will be examined in depth and possibly modified as part of the ÖkoRess II project (FKZ 3715323100).

References:

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8 Amalgamation of the results for the individual indicators

8.1 Introduction

In order to examine how the results of the raw material related assessment can be fed into the discussion of criticality and in order to ensure that the relevant connections can be made, it is now necessary to investigate how the individual results might be combined into a quantitative or qualitative amalgamation. Aggregation inevitably involves a loss of information, however. The authors therefore view the disaggregated form of the results of evaluation, e.g. as raw material related risk profiles, as the most valuable contribution of the proposed rating system.

The rating system described in this study is based on the assumption that, in spite of the limited number of indicators, the 11 selected indicators reflect the totality of significant environmental impacts and environmental hazard potentials and therefore present a complete and comprehensive picture of the environmental aspects of primary raw materials extraction.

The environmental hazard potentials can be integrated into the existing criticality model either as a third (environmental) dimension or as a partial indicator of supply risk on the security of supply axis. For both these approaches it is necessary to amalgamate the individual indicator values and produce a single value for each raw material.

There are many different ways in which this single value may be calculated. These will now be systematised and prioritised here, in the light of the subject matter under investigation. In the process, it is necessary to resolve some key questions of methodology as outlined below:

1. **Is a quantitative value required or is a qualitative result sufficient?**
   A quantitative analysis would make it possible to rank raw materials on a scale. (The environmental risk potential of raw material A is x% higher than that of raw material B.)
   The current criticality system is based on numerical values: one value for vulnerability (economic importance) and one for supply risk. Inclusion of the results of this study in the form of a third dimension of the criticality matrix, i.e. as an environmental dimension, would require a numerical, quantitative value. This approach using a three-dimensional criticality system has already been proposed by Graedel et al (2012). Similar considerations apply to integration of the environmental hazard potential into the supply risk: A numerical result would also be required for this.
   The calculation of a numerical aggregate value for the environmental dimension of criticality would have several advantages. On the one hand, numerical results can be represented along an axis, so it is then possible to rank raw materials in ascending or descending order. If necessary, the dividing lines between hazard classes can be defined as numerical threshold values. And these threshold values can be adjusted in the light of changes in the political, legal, or environmental conditions, without having to revise or modify the architecture of the system of assessment as such. Finally, if environmental considerations are to be regarded as a third dimension of criticality, the system requires a numerical coordinate for the third axis and a method for calculating the intersection with vulnerability in order to determine the criticality.
   However, unlike in the case of life cycle assessment, the basic data to be amalgamated, i.e. the individual values of the 11 indicators, are not numerical in nature. Apart from the data for indicators 9, 10, and 11, it is largely a question of qualitative assessment of environmental hazard potentials, which are described in the respective guidelines for measurement and exist in the form of low, medium, and high environmental hazard potentials. Numerical values for the assessment results would therefore only be substitutes for largely qualitative results. And there would need to be a convention for translating the qualitative assessment results into numerical values. Any such convention could only be derived subjectively. So the amalgamation of the results presented in

this study into a numerical result would then be subject to criticism for not being scientifically objective. This limitation must be born in mind where all numerical results of the amalgamation of data from this study are concerned. However, it is pointed out here that the established methods for determining supply risk and vulnerability in the context of the criticality debate follow exactly this path and translate largely qualitative indicators into quantitative values by means of such conventions.

2. **Is a relative weighting of the criteria helpful?**
   The weighting of individual criteria is used by the University of Augsburg, for example, for the description of the social risks of mining. But this is problematic because the relative weighting of the criteria depends on subjective assessment. This problem was addressed in the above-mentioned study by a large group of experts (Thorenz 2016), so averaging was possible using statistical analysis. But this did not solve the underlying problem, i.e. the subjectivity of the weighting.
   In addition, for the environmental indicators of this ÖkoRess project there is no obvious logic on which weightings might be based.
   If the individual results were to be amalgamated numerically without any weighting, all the indicators would effectively be weighted equally, which would only be permissible, if all the indicators contributed equally to the overall environmental hazard potential.
   The advantage of not weighting and amalgamating the indicators is that the individual results remain transparent. It has to be made very clear in this case that there can be no scientifically based prioritisation. Nor can the indicator results be understood to be weighted equally.
3. **Are there criteria which override all the others or are determining factors in the overall assessment (so-called "killer factors" or "active influences"[61])?**
   Among the ÖkoRess indicators, the "designated conservation areas and AZE sites" indicator is to be regarded as an "exclusion criterion", especially where "highly protected areas" are concerned. The Initiative for Responsible Mining Assurance (IRMA) also considers that these areas should be seen as "no-go-zones". However, this evaluation or exclusion of areas from mining is applicable to specific locations only (site-related assessment). In the raw material related assessment this could be taken into account by setting a strict threshold for the allocation of a high level of environmental hazard. (The extreme case would be for only one active mine to be located in such an area.) But this need not determine the overall rating of a raw material.
4. **What reciprocal relationships are there between the individual criteria?**
   For example: Copper ore is often associated with significant concentrations of heavy metals such as lead (Indicator 2). Furthermore, it occurs as sulphides, which is why there may be acid mine drainage (AMD) (Indicator 1). The storage of mine residues, especially from processing, may therefore lead to auto-oxidation and mobilisation of heavy metals. This well-known effect often has a serious impact on groundwater and surface waters, which should be classified as increasingly critical, the higher the competition over water use at the site (Indicator 7). The dispersal of the mobilised pollutants may be increased by a high risk of naturally induced accidents (Indicator 6).
   If the raw material is extracted by means of large-scale opencast mining (Indicator 4), then this interference with nature is to be assessed as even more critical when some of the mines are in designated protected areas (Indicator 8).
   The higher the cumulative raw materials demand of global production, as an indicator of the global level of activity for the extraction of the raw material (Indicator 10), the higher the sum potential of the individual hazard potentials, when most of them have a high rating.

[61] See the influence matrix method: https://de.wikipedia.org/wiki/Einflussmatrix

5. **How are these combinations of high environmental hazard potentials to be handled in the process of amalgamation?**
   If there is a coincidence of different risk factors, there may be an exponential increase in the overall hazard potential. For example, in the case of finely interwoven ores, which require fine milling and processing by means of leaching or flotation in an environment with a high risk of heavy rainfall, the safety of the tailings ponds may be threatened to such an extent that the consequences for the environment can be extremely high. The dam breach at the Ok Tedi gold and copper mine in Papua New Guinea in 1984 was a telling example of this (Seib, 2003).
6. **Are assessment levels or clusters helpful as a means of summarising individual indicators?**
   Generally speaking, clustering already appears in the early works of Graedel. The following general fields, which in turn included a variety of indicators, were selected for the supply risk axis: geological, technological, and economic field; social and regulatory field; geopolitical field (Graedel et al, 2012; Graedel et al, 2015). This logic has been followed in the evaluation matrix developed in the course of this project by the division into geology, technology, and natural environment (natural environment and environmental governance) levels.
7. **Is it possible to make use of the main groups of indicators (geology/deposits, technology, natural environment, environmental governance, and value chain levels) or would other clusters be more advantageous?**
   It is altogether possible to use these assessment levels as the basis of a summarised assessment. However, in order to benefit from experience with the assessment methods used in life cycle assessment and similar methodologies, clustering according to environmental goals would be more suitable for an overall assessment.
8. **What should be done with a high environmental hazard potential (red)? Should it be given extra weight? Or might it be sufficient to highlight the high environmental hazard potential ratings in the assessment summary?**
   The highlighting of a high environmental hazard potential would correspond with the distinction between "critical" and "non-critical" in the EU study (EU Commission, 2014) . The 3-stage differentiation into low, medium and high levels of environmental hazard potential has the advantage that attention would be given to a large number of medium environmental hazard potentials which may be mutually reinforcing.

In any case, a quantitative amalgamation requires either that all the indicators be given numerical values, or at least that the individual qualitative results be combined arithmetically (e.g. addition or multiplication of the number of indicators with high, medium, or low environmental hazard potential). Only then will the results be comparable.

Table 27 in the annex compares different methods of amalgamation and lists their advantages and disadvantages. A final selection of the method to be used may be made, taking into account the issues mentioned above.

8.2 Amalgamated qualitative assessment of environmental hazard potential

This chapter describes the procedure for amalgamating the results for the individual indicators into an overall environmental hazard potential using as examples the 5 selected raw materials, which were assessed in chapter 7 on the basis of the individual indicators.

8.2.1 Grouping of indicators according to environmental goals

The clustering according to the levels of geology, technology, natural environment, social environment, and value chain was very suitable as a structure for developing the methodology and assessing the individual indicators. And it is a structure which facilitates comparison of the individual results.

As the basis for an amalgamated assessment, however, it makes sense to cluster the assessment indicators according to environmental goals. This then forms the starting point for a step-by-step assessment. Such a clustering makes everything more easily comprehensible than a non-clustered assessment of individual indicators. And it makes it easier to weigh up the individual environmental hazard potentials in relation to each other. This is true regardless of whether a qualitative or quantitative amalgamation is chosen.

The following goals, to which the indicators at the various levels were assigned, can be identified in the raw material related assessment grid:

- Reduction of pollution risks
  This goal corresponds with the environmental target of protecting and conserving clean air, water, and soil, and protecting ecosystems, flora and fauna, and people from pollution or health hazards.
- Limitation of destruction of the natural environment
  This goal is about the conservation of biodiversity through protection against the destruction of habitats.
- Prevention of accidents induced by natural events
  Nature-related extreme events such as flooding, storms, landslides, and earthquakes may cause a significant increase in the spread of pollutants. The relevant indicator no. 6. “Risk of accident due to flooding, earthquakes, storms, or landslides" is therefore assigned to the assessment of this environmental goal: the reduction of pollution risks.

  An exception is made for the special rule included in this indicator regarding the assessment of risks in polar regions. This special rule stipulating an across-the-board rating of the situation in polar regions was necessary because the risk of accidents induced by polar storms and flooding in polar regions could not be shown on risk maps. However, a similar rule cannot suitably be applied where pollution risks are concerned, which is why it is omitted from the assessment of pollution risks.
- Prevention of water conflicts.
  This goal is concerned with the protection of water and therefore also the safeguarding of clean drinking water. If mines are largely in areas with high levels of competition over water use, the result is a high level of environmental hazard potential for water as a resource.
- Protection of valuable ecosystems
  If mining areas are situated within ecosystems which are especially in need of protection, they violate the protection objectives, the usual purpose of which is to conserve species diversity. Therefore, the associated indicator 8, “Designated protected areas and AZE sites", is assigned to the environmental goal of limiting destruction of the natural environment.
- Implementation of standards
  This objective is not an environmental goal as such, but rather an important contextual condition which influences the environmental hazard potential in relation to all the environmental goals. Potential environmental impacts are more likely to be reduced by adequate preventive measures, if environmental standards are reliably enforced in the main raw material producing countries. Even when the environment has already been affected or intrusions are inevitable, there is more likely to be an appropriate response in such countries in terms of limiting the impact on the environment and on the people who are affected. This goal and the associated indicator no. 9, "Environmental governance in the main producing countries", is therefore included as an influential contextual condition.

The following boundary conditions also have a significant influence and need to be taken into account in the amalgamation of the individual results:

- The situation in polar regions
  The special rule of an across-the-board rating of the risk of naturally induced accidents in polar regions has been excluded from indicator no. 6, “Risk of accidents induced by natural events” (see above). However, the polar regions are a particularly sensitive region where climate change is concerned. And highly dynamic surface processes are a major source of risk. If a significant proportion of the extraction of a particular raw material takes place in polar regions, this has to be taken into account along with the fact that the risk of accidents induced by polar storms and floods can lead to increased pollution risks. This is why "Location in polar regions" is included as an influential boundary condition.

- Value chain indicators - global significance
  The two value chain indicators - no. 10. Cumulative raw materials demand of global production ($CRMD_{global}$) and no. 11. Cumulative energy demand of global production (CED_{global}) - have been included to indicate the global order of magnitude of the environmental hazard potentials which were assessed using all the other indicators. Unlike in the case of the other indicators, the entire raw material - commodity value chain including raw material processing (e.g. smelting) was taken into account, in order to give at least a rough indication of the environmental hazard potentials of this stage in the value chain (see section 5.5 and Figure 2).

  Both these indicators, CED_{global} and $CRMD_{global}$, are therefore useful as indicators of the current global significance of a raw material and as a way of estimating the order of magnitude of the environmental hazard potential. They are therefore not assigned to a specific environmental goal, but are included in the assessment as influential boundary conditions (IBCs).

Table 13 provides a summary of the environmental goals to be taken into account in the amalgamated assessment, the influential boundary conditions, and the corresponding indicators.

Table 13 Grouping of indicators according to the most important environmental goals or as influential boundary conditions

Environmental Goals	Indicators
Reduction of pollution risks and the risks of increased pollution due to naturally induced accidents (“pollution risks”, for short)	No. 1: Preconditions for Acid Mine Drainage No. 2: Associated heavy metals No. 3: Associated radioactive substances No. 5: Use of auxiliary chemicals No. 6: Risk of accident due to floods, earthquakes, tropical storms, and landslides
Limitation of destruction of the natural environment and protection/conservation of valuable ecosystems (“natural environment”, for short)	No. 4: method of extraction No. 8: Designated protected areas and AZE sites
Prevention of water conflicts. (“water”, for short)	No. 7: Water Stress Index (WSI) and arid regions
Influential boundary conditions (IBCs)	**Indicators**
The situation in polar regions (“polar regions”, for short)	No. 6: Special rule for polar regions
Implementation of standards (“environmental governance”, for short)	No. 9: Environmental governance in the leading producing countries

Global extent of the EHP, $CRMD_{global}$ ("$CRMD_{global}$", for short)	No. 10: Cumulative raw materials demand of global production*
Global extent of the EHP, CED_{global} ("CED_{global}", for short)	No. 11: Cumulative energy demand of global raw material production

8.2.2 Combination of the individual indicator values relevant to each of the environmental goals and IBCs

The decision about how, for each of the environmental goals, to combine the individual results of the assessment of the relevant indicators, depends mainly on whether an assessment is to be made on the basis of a quantitative, numerical amalgamation or alternatively a qualitative, evaluative rating system has been chosen (see section 8.1).

As part of an assessment by means of numerical amalgamation, as is required for integration into the criticality system, this step can also be carried out by means of a numerical amalgamation of the indicators. Since no scientifically objective methodology exists, there would need to be some process of reaching agreement, in which the individual indicators (and, following that, the individual environmental objectives) were weighted in relation to each other (see section 8.1).

What follows here is a description of a qualitative method for combining the individual results for each environmental goal. The individual results (of the assessment of the indicators) are carried forward in a transparent manner and set alongside each other in such a way that the most important findings from the assessment of the individual indicators are not submerged in a subjective calculation.

The results of the relevant indicators need to be combined for each of the two environmental goals, "pollution risks" and "natural environment", and the IBCs. The environmental goal "reduction of water conflict" is based on only one indicator, so no combination is necessary.

8.2.2.1 Environmental Goal: "Reduction of pollution risks"

The indicators which are relevant to the environmental goal "prevention of pollution risks" are structured in different ways.

The four indicators

- 1. Preconditions for Acid Mine Drainage
- 2. Associated heavy metals
- 3. Associated radioactive substances
- 5. Use of auxiliary chemicals

are indicative of specific pollution risks arising from the basic geological conditions (1 to 3) or the methods of processing (4). The risk of associated heavy metals being emitted rises steeply, if the preconditions for acid mine drainage also exist.

Indicator no. 6. "Risk of accidents induced by floods, earthquakes, tropical storms, and landslides", on the other hand, refers not to particular pollution risks but rather to characteristics of the natural environment which significantly increase the risk of pollutants being dispersed or increase the scale of the release of pollutants which are emitted during normal operations.

If no more than one indicator is assessed as having a high environmental hazard potential (EHP), both the following possibilities are excluded: firstly, the possibility of an unfavourable combination of high EHP for both indicators 1 and 2; and secondly, the possibility of one of these indicators, which represent an existing pollution risk, being coupled with a high rating for indicator no. 6.

The environmental goal "prevention of pollution risks" is therefore assigned a high environmental hazard potential, if two or more indicators exhibit a high environmental hazard potential. In such a case, either one of the unfavourable combinations mentioned above has arisen, or the environmental hazard potential is aggravated by a "second" pollution risk. A high hazard potential is also assumed, if alongside a single high EHP all the other indicators exhibit a medium EHP.

The environmental goal "prevention of pollution risks" is credited with a low environmental hazard potential (EHP), if no more than one indicator exhibits a medium environmental hazard potential and all the other indicators are credited with a low environmental hazard potential.

All other possible combinations are assigned a medium environmental hazard potential.

Table 14 Rules for consolidated assessment of the environmental goal "prevention of pollution risks"

EHP	Rules
Low	No more than one indicator with medium EHP and all other relevant indicators[62] with low EHP
Medium	One or more indicators with low EHP and no more than one indicator with a high EHP or more than one indicator with medium EHP
High	Two or more indicators with high EHP or one indicator with high EHP and all others with medium EHP

EHP = environmental hazard potential

Table 15 shows, as an example, the application of these rules to the five raw materials which were studied. It should be borne in mind that the values for indicator no. 6 "risk of naturally induced accidents" are still provisional and that they have been calculated for the five raw materials studied as an example. The final determination of limits for low, medium, or high EHP for this indicator can only be carried out as part of ÖkoRess II. This will then be based on data for the raw materials which are to be examined.

Table 15 Comparison of the results of the assessment for the environmental goal "prevention of pollution risks", using the assessment of the five raw materials studied, as an example.

Environmental goal "pollution risks"	Environmental hazard potential (EHP)				
Indicators/raw materials	Copper	Gold	Aluminium	Tungsten	Graphite
1. AMD	High	Medium	Low	Medium	Low
2. Associated heavy metals	High	Medium	Medium	Medium	Low
3. Associated radioactive substances	Medium	High	Medium	Medium	Low
5. Use of auxiliary chemicals	High	High	High	Medium	Medium
6. Risk of naturally induced accidents*	High	Low	Medium	Medium	Low

[62] The relevant indicators are nos. 1, 2, 3, 5, and 6.

Results of assessment of pollution risks	High	High	Medium	Medium	Low

* interim assessment not including the situation in polar regions

8.2.2.2 Environmental Goal "Limitation of destruction of the natural environment"

As regards the environmental goal "Limitation of destruction of the natural environment", a high EHP for indicator no. 4 "Method of extraction" is indicative of unavoidable direct destruction of the natural environment by large-scale opencast mining. There is therefore no better way of assessing this environmental goal than by using this indicator. If both indicator no. 4 and indicator no. 8 exhibit a medium EHP, this also leads to a high EHP for the environmental goal.

A high EHP for the environmental goal "Limitation of destruction of the natural environment" also results if designated protected areas and AZE sites are significantly affected (high EHP for indicator no. 8).

A low EHP is only assigned if both indicators exhibit a low EHP.

A medium EHP represents a combination of a low and a medium EHP rating.

Table 16 Rules for consolidated assessment of the environmental goal "limitation of destruction of the natural environment"

EHP	Rule
Low	Both indicators exhibit low EHP
Medium	One of the two indicators exhibits a medium EHP and the other exhibits a low EHP
High	Both indicators assigned a medium EHP or at least one exhibits a high EHP

EHP = environmental hazard potential

Table 17 shows, as an example, the application of these rules to the five raw materials which were studied. It is evident from this example of the raw materials studied that it is possible to make a clear and indisputable assessment of the EHP regarding destruction of the natural environment. According to this, copper, gold, and aluminium exhibit a high EHP, whilst tungsten and graphite both exhibit a low EHP.

Table 17 Comparison of the results of the assessment for the environmental goal "limitation of destruction of the natural environment", using the assessment of the five raw materials studied, as an example.

Environmental goal "natural environment"	Environmental hazard potential (EHP)				
Indicators/raw materials	**Copper**	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
4. Method of extraction	Medium	Medium	High	Low	Low
8. Designated protected areas and AZE sites	High	High	Medium	Low	Low

Results of assessment of natural environment	High	High	High	Low	Low

* interim assessments

8.2.2.3 Influential boundary conditions

Reference to the IBCs makes fine adjustments possible. It should be borne in mind that the assessment of the situation in polar regions is provisional and has been undertaken for the five raw materials studied as an example. As in the case of the other indicators for the natural environment, the "Limits" have been set simply on the basis of the mean values of the weighted distribution[63]. According to this assessment, copper and gold exhibit a medium EHP, whilst bauxite, tungsten, and graphite all exhibit a low EHP. The final assessment for this indicator can only be undertaken as part of ÖkoRess II on the basis of the results for the 51 raw materials.

As with the individual environmental goals, a preliminary overview of the IBCs now follows. Rules for this are shown in Table 18. An important premise on which the assessment of the IBCs is based is the fact that the $CRMD_{global}$ and the CED_{global}

- reflect the global order of magnitude of the mining and processing (including smelting, etc.) of a raw material and therefore the scale of the environmental hazard potentials which are likely to be involved in the mining and processing of the raw material.
- The $CRMA_{global}$ can also serve as a proxy indicator of the quantity of mining residues.

Table 18 Rules for the consolidated assessment of the influential boundary conditions

EHP	Rule
Low	Three indicators with low EHP, on condition that both the $CRMD_{global}$ and the CED_{global} exhibit no more than a medium EHP
Medium	All possible combinations between low and high
High	Two indicators with a high EHP or at least one indicator with a medium EHP combined with one of the indicators, $CRMD_{global}$ or CED_{global}, exhibiting a high EHP.

EHP = environmental hazard potential

In the case of the indicator for environmental governance, special account is taken of the fact that this especially increases the impact of mining which is environmentally damaging. In principle, for the overall global assessment, a high EHP for environmental governance can only have a negative influence on the results for the environmental goals if it is combined with a high EHP for the $CRMD_{global}$ or the CED_{global}.

The assessment results for copper, gold, and aluminium in relation to the IBCs differ only as regards the situation in polar regions: In the case of copper and gold, the proportion of total mining activities which take place in polar regions is higher than the average for the five raw materials studied, but it is less than the average in the case of aluminium (see Table 19).

[63] A special rule has been applied to the situation in polar regions, i.e. the assignment of a medium hazard potential across the board. The mean values of the weighted distribution results are 97% low and 3% medium risk potential.

Table 19 Comparison of the results of the assessment for the influential boundary conditions (IBCs), using assessment of the five raw materials studied, as an example.

	Environmental hazard potential (EHP)				
IBCs/raw materials	**Copper**	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
Polar regions*	Medium	Medium	Low	Low	Low
Environmental governance	High	High	High	High	High
$CRMD_{global}$	High	High	High	Medium	Low
CED_{global}	High	High	High	Medium	Low
Assessment results for IBCs	High	High	High	Medium	Low

* provisional assessments

8.2.3 Combination of the results for the three environmental objectives

If a comparative, qualitative assessment of the EHPs of the raw materials studied is adequate for the results to be applied as desired, the process described in the section "Comparative overall assessment on the basis of reasoned argument" (see below) is recommended. This applies especially if there is only a limited number of raw materials, the EHPs of which are to be compared in relation to each other. The result is a ranking of the raw materials according to their EHP, although the possibility of two or more raw materials having the same ranking cannot be ruled out.

If there is a large number of raw materials to be assessed, an overall comparison based only on reasoned argument may be impractical. In this case, for the purpose of obtaining an overall result, qualitative combination of the results for the individual environmental goals is recommended. As in the case of the individual indicators and environmental goals, each raw material is assessed as having a low, medium, or high overall environmental hazard potential (oEHP).

Whichever one of the two methods is chosen, it is helpful to classify or rank the environmental goals according to their ecological importance. Ecological importance is meant in terms of a hierarchical ranking of environmental goals, according to how serious the threat to each one of them is in comparison with the others. This ranking is dependent on subjective judgements and should therefore be undertaken through social discourse as far as possible, as in the case of numerical weightings. A ranking in terms of ecological importance is therefore only possible here as an example from the perspective of those undertaking the research. The criteria to be used for this ranking are the global importance of the environmental goal and the severity of the current global threat to the goal, (analogous to "degree of threat to the environment" and "distance from environmental goal" according to UBA (1999)). Following the UBA method for the evaluation of life cycle assessments (UBA 1999), 5 classes are envisaged: very low, low, medium, high, very high.

From the point of view of the researchers, all three of the environmental objectives with which we are concerned are of high or very high ecological importance. The only distinction to be made is therefore between high and very high ecological importance.

The following classification is therefore defined for application in this study:

- **Very high ecological importance**[64]
  Global impact; in some cases irreversible damage on a large scale is expected; long distance from attaining the goal of protection; and planetary limits (Rockström et al, 2009; Steffen et al, 2015) exceeded or very nearly exceeded
  => Natural Environment - covers, amongst other things, biodiversity (high global importance and upper planetary limits far exceeded) and changes in land use (high global importance and lower planetary limit exceeded)
- **High ecological importance**
  Impact at regional level; in some cases irreversible damage on a large scale is expected; possible impact on several factors which are in need of protection (e.g. human health, water, soil); distance from attaining the goal of protection is medium to high; planetary limits have not been exceeded
  => competition over water use (may be of considerable importance regionally, global importance not so high, planetary limits have not been reached)
  => pollution risks (may be of considerable importance regionally, global importance not so high, planetary limits have not yet been defined)

8.2.3.1 Comparative overall assessment on the basis of reasoned argument

The results of the assessment of the environmental goals form the basis of a comparative assessment based on a comparison of the results, in which the influential boundary conditions are also taken into account.

The first step, for each of the raw materials studied, is an examination of the rating in relation to the environmental goal of very high ecological importance.

[64] The environmental goal of climate protection is also of very high ecological importance - due to the global impact and the serious and irreversible nature of the anticipated consequences of climate change. The distance from the environmental goal is considered to be high, because the lower planetary limit has been exceeded. The method presented here does not include an adequate indicator for climate protection, because there is no data available, which would be suitable for analysis, and because climate protection is not considered to be one of the main problems associated with raw materials extraction.

The second step is to establish whether the ratings in relation to the environmental goals of high ecological importance confirm the result for the environmental goal of very high ecological importance.

The influential boundary conditions (IBCs) can then be brought into the equation for fine-tuning.

Application of the method to the five raw materials under study, as an example

As expected, the comparison in relation to the environmental objective of very high ecological importance is clear:

Copper, gold, and aluminium, each with a high EHP, are in first place ahead of tungsten and graphite, both of which exhibit a low EHP.

Table 20 Comparison of the results of the assessment for the environmental goals of very high ecological importance, using the assessment of the five raw materials studied, as an example.

	Environmental hazard potential (EHP)				
Environmental goals/raw materials	**Copper**	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
Natural Environment	High	High	High	Low	Low

If one considers the results of the assessments in relation to the environmental goals of high ecological importance, the assessments of both aluminium and tungsten differ from each other and are also at variance with the assessments in relation to the environmental goal of very high ecological importance, whereas the results for copper and gold are all in accordance. This results in a new comparison being made between gold and aluminium. Where competition over water use and pollution risks are concerned, aluminium clearly performs much better than copper and gold. The ranking is therefore adjusted as follows:

Of the raw materials studied, copper and gold exhibit the highest overall environmental hazard potential (oEHP), followed by aluminium. Graphite comes next. Tungsten exhibits the lowest preliminary rating (oEHP).

Table 21 Comparison of the results of the assessment for the environmental goals of high ecological importance, using the assessment of the five raw materials studied, as an example.

	Environmental hazard potential (EHP)				
Environmental goals/raw materials	**Copper**	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
Pollution risks	High	High	Medium	Medium	Low
Water	High	High	Low	Low	High

* provisional assessments

The rankings of copper, gold, and aluminium in relation to the environmental goals are unaffected by the inclusion of the IBCs, although in the case of copper and gold the result for the environmental goals is fully confirmed, whereas the overall environmental hazard potential (oEHP) for aluminium is increased even further by the high EHP of the IBCs. In the case of tungsten, the result for the environmental goals is largely confirmed. And in the case of graphite, the low EHP of the IBCs results in an improvement, so that graphite ends up on an equal footing with tungsten.

Table 22 Comparison of the results of the assessment for the influential boundary conditions (IBCs), using the assessment of the five raw materials studied as an example.

	Environmental hazard potential (EHP)				
IBCs/raw materials	**Copper**	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
IBCs	High	High	High	Medium	Low

According to this, the result of the final ranking is that, in a comparison of the five raw materials studied, copper and gold both exhibit the highest overall environmental hazard potential (oEHP), followed by aluminium. Tungsten and graphite turn out to have the lowest oEHP of the five raw materials. They have a roughly equal ranking.

8.2.4 Combined ranking of raw materials

If a ranking of the raw materials studied through comparative assessment on the basis of reasoned argument fails to produce a clear result because of the number of parameters involved, or the resultant ranking is considered to be inadequate, a qualitative combination of the results of the individual environmental goals into an overall result can be carried out as an alternative or additional assessment. As in the case of the individual indicators and environmental goals, each raw material is assessed as having a low, medium, or high overall environmental hazard potential (oEHP).

Table 23 Rule for the combined assessment of the environmental goals to produce a provisional overall environmental hazard potential (poEHP)

poEHP	Rule
Low	Medium EHP for no more than one environmental goal of high ecological importance, and low EHP for all other environmental goals.
Medium	All possible combinations between low and high
High	High EHP rating for two environmental goals or high EHP for the environmental goal of very high ecological importance or high EHP for one environmental goal of high ecological importance and medium EHP for all other environmental goals

poEHP = preliminary overall environmental hazard potential

In Table 25 the “interim result for environmental goals” line shows the results of the application of this method, using the five raw materials studied as an example.

The ratings of the IBCs must now be taken into account in order to deduce the final result from the interim result for the environmental goals. Table 24 shows the rules for applying the ratings for the IBCs to the interim result for the environmental goals.

Table 24 Rule for combined assessment of the interim results for the environmental goals and the ratings for the ICBs to produce an overall environmental hazard potential (oEHP)

oEHP	Rule
Low	The interim result for the environmental goals exhibits a low poEHP and the IBCs rating is a low or medium EHP or the interim result for the environmental goals exhibits a medium poEHP, for which no environmental goal was assigned a high EHP and the ICBs rating is a low EHP
Medium	The interim result for the environmental goals exhibits a medium poEHP and the IBCs rating is a low or medium EHP or the interim result for the environmental goals exhibits a high poEHP, whereby no more than one environmental goal of high ecological importance is assigned a high EHP, and the IBCs rating is a low EHP whereby no single IBC has a high EHP rating.
High	All possible combinations between low and high

Since the results for all the environmental goals and the IBCs can be seen clearly at a glance in the results table, the transparency of the findings in relation to the environmental goals is fully maintained. Although the final classification shows copper, gold, and aluminium all as having been assigned a high oEHP, it is immediately clear from the illustration that all the individual results are the same for copper and gold whereas aluminium exhibits a medium EHP for the environmental goal “pollution risks” and even a low EHP for the environmental goal “water”. Tungsten is assigned a low oEHP in the interim assessment for the environmental goals, and this is confirmed when the ICBs are included in the assessment. The interim rating for graphite after evaluation of the environmental goals is medium oEHP, and this is also confirmed when the IBCs are taken into account. High EHP ratings in relation to the environmental goal “water” and the IBC “environmental governance” militate against a low EHP rating.

Overall, the final evaluation on the basis of the provisional assessment criteria for the environmental level (environmental goal “pollution risks” and IBC “polar regions”) and the social level (IBC “environmental governance”) is not yet conclusive. ÖkoRess II will include examination of whether or not the system of assessment needs to be adjusted on the basis of the final specifications for the individual assessments, so that the different situations of the raw materials studied can be portrayed as accurately as possible.

Table 25 Combination of the assessment results for the environmental goals in order to deduce an oEHP, using the assessment of the five raw materials studied as an example.

Raw materials	Copper	Gold	Aluminium	Tungsten	Graphite
Environmental Goals	**Environmental Hazard Potential (EHP)**				
very high ecological importance					
Natural Environment	High	High	High	Low	Low
high ecological importance					
Pollution risks	High	High	Medium	Medium	Low
Water	High	High	Low	Low	High
	provisional overall environmental hazard potential (poEHP)				
Interim result for environmental goals	**High**	**High**	**High**	**Low**	**Medium**
	Copper	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
IBCs	**Environmental Hazard Potential (EHP)**				
Polar regions	Medium	Medium	Low	Low	Low
Environmental governance	High	High	High	High	High
$CRMD_{global}$	High	High	High	Medium	Low
CED_{global}	High	High	High	Medium	Low
Assessment result IBCs	High	High	High	Medium	Low
	Overall environmental hazard potential (oEHP)				
Overall result	**High**	**High**	**High**	**Low**	**Medium**

* provisional assessments

In order to highlight the differences between various raw materials which have been given the same oEHP ranking, the ranking according to the comparative assessment on the basis of reasoned argument may also be brought into play[65]. As described above, the ranking according to hazard potential of the raw materials with a high oEHP puts copper and gold before aluminium. For tungsten and graphite no further ranking is necessary, since they are each of them the only raw material to be classified within their own assessment level.

[65] It is also conceivable that one might introduce additional assessment levels (low - low to medium - medium - medium to high - high), resulting in an overall assessment with four or five grades.

8.3 Results of the raw material related assessment carried out for this study

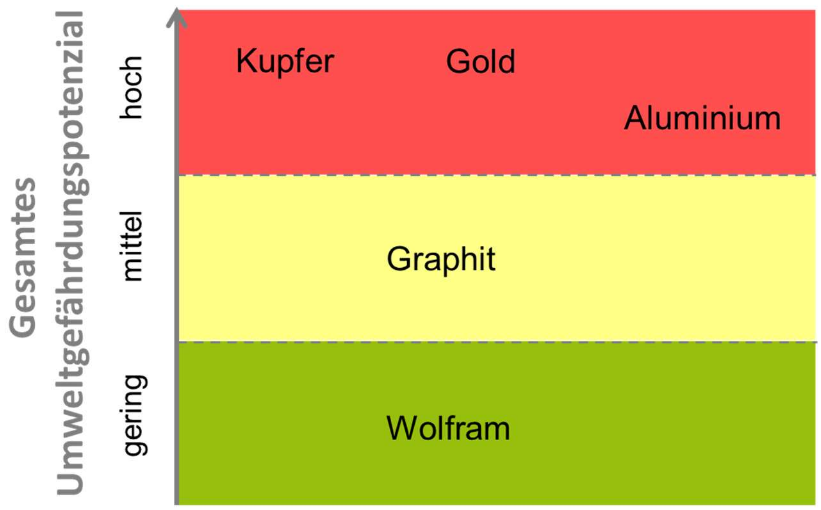
For this current study a qualitative assessment of hazard potential was chosen. This involves combining the classification of raw materials according to high, medium, or low overall environmental hazard potential (oEHP) with a ranking of the raw materials within these three classes on the basis of reasoned argument.

The evaluation, according to this method of assessment, of five raw materials serves as an example:

High oEHP	Rank 1: Copper and Gold
	Rank 3: Aluminium
Medium oEHP	Rank 1: Graphite
Low oEHP	Rank 1: Tungsten

One way in which this result can be displayed graphically, is shown in Figure 17.

Figure 17 Results of a preliminary ranking of the 5 raw materials studied on the basis of an aggregated assessment, shown as an example



Other methods for combining the results for the individual indicators by means of numerical aggregation are described briefly in the annexe.

8.4 Possible applications and limitations

The results of the aggregated assessment, the classification of raw materials into low, medium, and high hazard potential, together with a further ranking within the classes, can be used both as an assessment of sustainability and as an assessment of criticality.

For use in the assessment of sustainability, the results of the aggregated assessment provide information about which abiotic primary raw materials deserve special attention, due to a high overall environmental hazard potential from mining and processing. The results for the individual indicators prior to aggregation can be used to identify appropriate measures for the mitigation of the hazard potentials.

As regards an assessment of criticality, the ordinal scale for the oEHP (Figure 17) can in principle be presented to any interested party, such as:

- economists, companies, etc. for the assessment of critical raw materials;

- economists, companies, etc. for the assessment of strategic raw materials (future technologies, environmental technologies).

This assessment has its limitations: transparency is lost through the aggregation of the individual results; and poor decisions may be made, if there is no deeper investigation into the root causes of high oEHPs.

An additional limitation is the fact that the assessment results are not suitable for a comparative evaluation of raw materials. This would require some relation to defined quantities of raw materials and analysis of the entire life cycle - including all the stages of manufacture, use, and disposal - of products made from these raw materials,. However, the raw material related ÖkoRess assessment only considers the first steps of global value chains up to the production of standardised commodities with a focus on the extraction and processing of primary raw materials. The CED_{global} and $CRMD_{global}$ indicators are representative of the global significance and order of magnitude of the environmental hazard potentials.

Integration of the assessment into the thinking about criticality is described in the following section.

9 Integration of the results into the criticality concept

Numerous research projects have been carried out in recent years, due to worries about the availability of raw materials becoming increasingly restricted as a result of price increases or growing scarcity. These research projects have specifically entailed investigation of the supply risks of non-fuel raw materials and the vulnerability of economic systems to interruptions in the supply of these raw materials. See, for example: National Research Council of the National Academies (2008); EU Commission (2010 and 2014); Graedel et al (2012 and 2015); and Coulomb et al (2015). In the criticality matrix which has been developed in the meantime, the two dimensions, "supply risk" and "vulnerability", are the two axes in a coordinate system. Indicators for supply risk include, for example, the degree to which raw material extraction is concentrated in particular countries or corporations, and governance in the main producing countries. Indicators for vulnerability usually reflect the economic importance of the raw materials for the economic system and sometimes the degree of adaptability in response to changes in the supply of raw materials (e.g. relative importance in manufacturing, quantities used, accessibility, and feasibility of substitution). The criticality matrix evaluates the relative scarcity from the point of view of a system which uses the raw material (e.g. a company or a national economy). High criticality means that there is a high risk of (exogenous) disruption of the supply of a raw material, e.g. unexpected price hikes or even interruptions of supply, and this is combined with a high degree of (endogenous) vulnerability to such disruptions of supply due to high susceptibility and low adaptability.

So far environmental issues have only been addressed in a few works and have only been given limited attention. In National Research Council of the National Academies (2008), for example, the possibility of limited availability due to competing uses is addressed under the heading of "environmental and social availability". In the EU's first criticality study (EU Commission, 2010) an assessment of environmental issues (in addition to supply risk due to poor governance) was included in a consideration of "supply risk due to low environmental standards". The assessment was carried out using the Environmental Performance Index (EPI), the logic being that a risk of disruption of supply arises when countries with low environmental standards introduce stricter environmental regulations. The EPI is not a suitable indicator, however, due to the lack of reference to mining. And this assessment was not included in the 2014 study of the EU Commission (2014). In the OECD study (Coulomb et al, 2015) environmental risks are addressed as "externalities" in the discussion of the limitations of the methodology. Once again, the logic here is that the introduction of higher environmental standards may threaten supplies, so that it may be necessary to include environmental costs[66] in the method of assessment.

Although very little has been done about it so far, there is widespread recognition that environmental issues cannot be disregarded altogether, when it comes to the question of which raw materials are to be regarded as critical, i.e. in short supply, because of socio-economic forces. There is a growing number of reasons for giving attention to environmental issues, especially when the following factors are taken into account: long-term increases in environmental impact as a result of the extraction of lower grade ores; deeper deposits; more complex ores; the growing trend towards large-scale opencast mining; and the increased incidence of mining activities in environmentally sensitive regions.

However, the question as to how environmental issues are to be taken into account in the discussion of criticality has yet to be answered. There are a lot of interrelated factors to be taken into account:

[66] The internalisation of external costs - in this case the costs of implementing environmental standards

- So far, in discussions about the aims and objectives of the various concepts of criticality, special emphasis has been given to security of supply. According to VDI 4800, Sheet 2, point 6, the objective of the criticality analysis is: "to identify raw materials of a raw material-using system (reference system) that serve essential functions for this system while their supply is associated with risks." Given this objective, environmental issues are only relevant to the criticality debate in so far as they are an acute cause of heightened supply risk or are likely to lead to heightened risk in the future. From this perspective, which focuses on scarcity, inclusion (of environmental issues) in the spectrum of supply risks (as in EU Commission, 2010, for example) would seem to be the obvious approach. In what would be an ideal world from an environmental point of view, where environmental costs are fully internalised through effective governance (environmental standards), environmental issues would not have to be considered as part of criticality analysis, because they would be completely factored into the equation economically and would influence the behaviour of relevant actors accordingly. However, this would not give sufficient weight to the importance of the environmental impacts of mining, which, from a sustainability point of view, require attention even if supply risks are not affected.
- If sustainability issues were to be taken into account only in so far as they have an impact on the security of supply, this would mean that, in the short and medium term at least, the impact of environmental problems on the vulnerability of the supply of raw materials would be strongest where measures are taken to protect the environment. In the long term this situation could change, so that the regions in which environmental issues have been disregarded have more influence on security of supply. The situation could then escalate to such an extent that mining is no longer possible in such regions. The situation is similar where social issues are concerned.
- It is therefore important, from the point of view of sustainability, for the aims of criticality analysis and the discussions about risks to the supply of raw materials to be aligned with the general aims of resources policy - and to incorporate both social and environmental criteria. The aim formulated by ProgRess II, for example, is: to secure the sustainable supply of raw materials. A further aim is to contribute to (among other things): the extraction of minerals and fossil fuels becoming more environmentally friendly; a strengthening of environmental, social, and transparency standards in the global raw materials sector; and the creation of more sustainable supply chains (BMUB, 2016). Gandenberger at al (2012) summarise the goals of Germany's raw materials policy as follows: security of supply, price stability, market transparency, non-discrimination, reduced consumption of raw materials, improvement of social conditions in the mining industry, reduced environmental pollution caused by raw materials extraction, and responsibility being taken for the situation in resource-rich developing countries.
- A suitable definition of the goal of criticality analysis of raw materials should read as follows, for example: "to identify raw materials of a raw material-using system (reference system) that serve essential functions for this system while their sustainable supply is associated with risks." Under this premise, the introduction of a third dimension would serve this purpose, because the importance of environmental issues and related social issues can be taken into account in their own right.
- It also seems to be important to highlight the conflicting aims, mentioned above, of raw materials and resources policy. For example, where the promotion of sustainable use of natural resources is concerned, the objective of price stability is counter-productive. This is because compliance with environmental standards, which is both desirable and necessary, would, presumably through the internalisation of external costs, lead to a significant increase in commodity prices. This would have a negative impact on the security of supply, according to

the current definition, as set out in the above-mentioned EU study of critical raw materials published in 2010. On the other hand, reduced consumption of raw materials, which is necessary from the point of view of sustainability, is all the more difficult to achieve, the lower commodity prices are and/or the less environmental costs are included in price-setting.

- It should also be borne in mind that disruption of the secure supply of essential high-tech raw materials could lead to imports of essential environmental protection equipment becoming more expensive and/or being hindered, delayed or even prevented. And it is necessary to bear in mind that environmental issues should be integrated into criticality analysis, so that appropriate measures to promote the long-term sustainability of supply of raw materials can be developed accordingly.

The inter-relationships which have been described lead to the conclusion that environmental issues should be integrated into criticality analysis as a separate dimension. It does not make sense to include environmental issues as an aspect of supply risk, because their independent significance is then lost and it is no longer possible to identify the underlying reasons for a high environmental hazard potential.

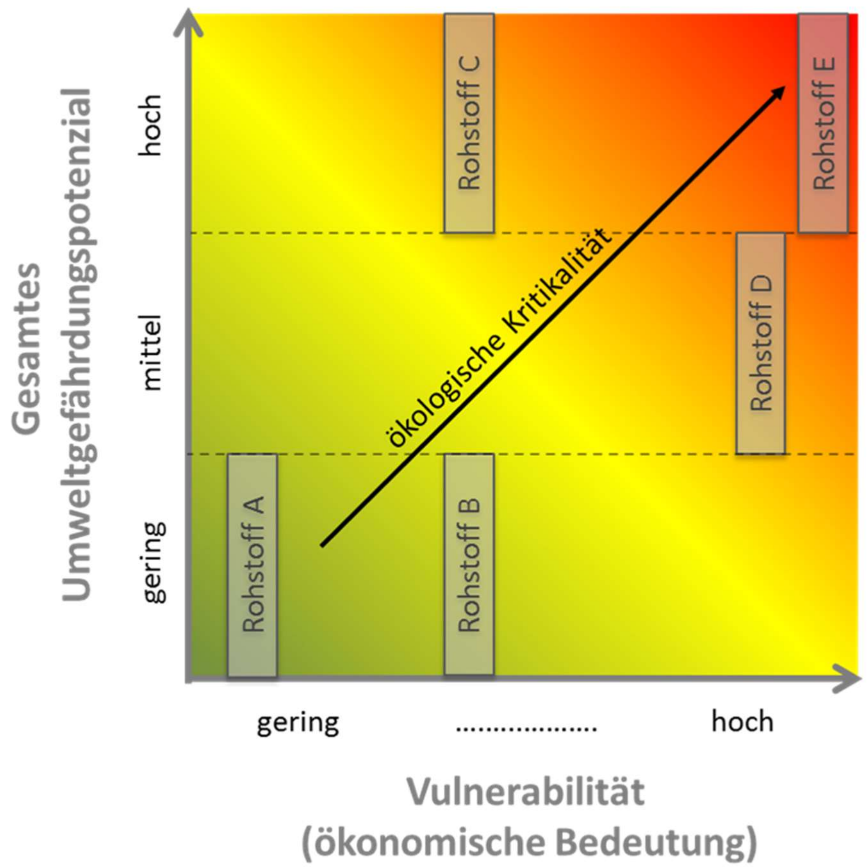
The qualitative combination of the results in Chapter 8, to create an aggregate ranking, makes it possible to integrate the results into the criticality analysis. The ordinal scale can, in principle, be applied to any reference system. The qualitative classification needs to be given further thought, however, in so far as there is no similar 3-point scale for vulnerability[67].

For example, the EU criticality study (EU Commission, 2010 and 2014) only distinguishes between critical and non-critical, which, according to Kosmol et al (2017), is positive as regards ease of communication, but contradicts the idea of criticality as a relative concept. The values on the vulnerability axis (economic importance) lie between 0 and 10. According to the results obtained so far, raw materials which are classified as critical have a value > 5. Raw materials with a high oEHP could therefore be entered with a value for vulnerability > 5. Where integration into the EU criticality analysis is concerned, it should also be noted that the environmental governance indicator is currently represented by two Worldwide Governance Indicators and the supply risk of the EU criticality study is also evaluated partly on the basis of Worldwide Governance Indicators. However, the environmental governance indicator does not have any influence as an influential boundary condition on the results of the evaluations which have been obtained so far. Furthermore, various aspects of governance will be examined in greater depth and developed further in the ÖkoRess II follow-up project.

One way of comparing oEHP and vulnerability is shown in Figure 18. The combined representation of the two dimensions is a measure of environmental criticality, which is higher the nearer the raw material appears to the top right-hand corner of the coordinate system. The example shown is based on the EU criticality study (raw materials classified as critical are located to the right of the middle of the x-axis: vulnerability values > 5 on a scale of 0-10, see above). According to this, the raw materials A and B are not environmentally critical but raw material E is environmentally critical. To start with, it is possible to state, as regards the raw materials C and D (which serve as an example for what follows) that raw material C, like raw material B, is not of high economic importance, but does exhibit a high oEHP. Raw material D, on the other hand, is of high economic importance, but exhibits only a medium oEHP. It can be assumed that these two raw materials exhibit a similar degree of environmental criticality.

[67] For the ÖkoRess II follow-up project, an increase in the number of levels on the oEHP scale to 5 is also under consideration. This would facilitate a more differentiated ranking of the raw materials.

Figure 18 An example of the representation of oEHP in relation to vulnerability



Source: Own illustration based on Kosmol et al (2017)

By determining the level of environmental criticality it is possible to establish whether more attention needs to be given to raw materials which have not been classified as critical until now, and to identify the raw materials which have been classified as critical and also exhibit a high environmental hazard potential.

The importance or the possible consequences of high environmental criticality may be a result of hazard potentials, on which the oEHP is based, actually becoming reality and causing environmental damage. Alternatively, the probability of such occurrences may be reduced as far as possible by appropriate measures (technical safety measures, environmental standards, exclusion zones). Both of these eventualities can lead to reduced security of supply, as has been described.

Standards of governance can provide an indication as to which of these two scenarios is more likely to occur:

- Where there is poor governance, there is a higher risk of environmentally induced social conflict, which may lead to an interruption of mining activities → Depending on the extent to which production is concentrated in a small number of producing countries, there may be bottlenecks in the supply of raw materials, so that they become more expensive because of shortages of supply.
- Where there is good governance, it is to be expected that high environmental hazard potentials will be tackled by the implementation of appropriate measures → raw materials become more expensive ("scarcer") as a result of this internalisation of external costs.

From the point of view of the evaluation of environmental criticality and from the point of view of an assessment of sustainability, the following conclusions may be drawn from these reflections: A high level of environmental criticality indicates that support needs to be given to the enforcement of environmental standards in the mining industry. This is necessary - even though it might lead to reduced security of supply in the short to medium term - in order to counteract any shortages in the long-term, which might otherwise be caused by potentially irreversible damage to the environment.

10 Conclusions and recommendations for action

With this methodology for the raw material related evaluation of the environmental hazard potentials involved in the extraction of abiotic primary raw materials there is now a newly developed instrument for the assessment and evaluation of the environmental hazard potentials involved in the extraction of abiotic raw materials at the global level.

The method is based on a large number of existing scientific analyses and reports, but the methodological approach is innovative. It is built up step-by-step and has been developed through iterative processes involving a single approach to the evaluation of individual sites on the one hand and mining waste on the other hand. It has also been adapted and validated on the basis of practical examples. In spite of being intentionally limited to a small number of indicators, the methods measure up to the wide range of geological, technical, and local site conditions and show the variety of possible environmental impacts from mining. The scale of the environmental impacts is also illustrated by many of the 40 case studies which have led especially to the realisation that the effects of mining are very varied in terms of both nature and magnitude and depend not only on the raw material being extracted but also on site-related factors and whatever environmental protection measures may be taken. It is noticeable that while environmental protection measures are taken in many places, these are usually not sufficient to reduce all the environmental effects to the minimum possible or to internalise environmental costs to a large extent. At the same time, one can find mines in many regions of the world, which disregard environmental protection measures altogether. Special importance is therefore attached to the quality of environmental governance.

10.1 Evaluation of the results of the assessment, including a discussion of their limitations in terms of what they tell us

The **raw material related assessment in** accordance with the method presented here allows the following results to be presented:

- An environmental hazard potential with 11 indicator ratings in three categories (low, medium, and high environmental hazard potential).
- In addition to this, it is possible, using the methodology proposed and developed here, for an aggregated result for each raw material to represent the overall environmental hazard potential.

The rating system is designed in such a way that the indicator ratings can be evaluated without on-site surveys and by professionals who do not necessarily have to have a background of experience specifically in mining. This naturally leads to over-simplification and therefore to the results being of limited value. The following limitations have to be taken into account:

- The only meaningful results are the environmental hazard potentials of individual raw materials.
- The methodology does not allow any statements to be made about the scale of actual damage done in the event of an accident or by the emission of pollutants during normal operations.
- Bearing these limitations in mind, the results of the assessments of several raw materials may be used for comparative classification or ranking, e.g. in criticality analysis or in the assessment of sustainability. It can be seen from the ranking which raw materials exhibit a higher global environmental hazard potential than others as regards extraction. This makes it possible to set priorities as regards which raw materials need to be given special attention in resource and environmental research, e.g. through a focus on more economical use of particular raw materials.

- The results are not suitable for use in life cycle assessments or in making decisions about the substitution of raw materials, because the assessment is based on the total global production of each raw material and not on defined amounts. It still only makes sense to draw conclusions in relation to products while taking the whole life cycle into account. However, the environmental hazard potentials of extraction can be used as a supplement to life cycle assessments to counteract the gaps in the data and knowledge regarding extraction in particular.
- The amalgamated results of the raw material related assessment are even more simplified and no longer contain detailed information about the indicator ratings and specific hazard potentials on which the assessment is based. The only meaningful way in which it is possible to work out what measures could be taken to mitigate hazard potentials (in the context of a sustainability assessment) is to use the results for the individual indicators before they have been amalgamated. In criticality analysis it is possible to integrate the overall environmental hazard potentials using an ordinal scale. If the combination (of overall environmental hazard potentials) with the vulnerability of a reference system results in an independent environmental dimension, it is possible to determine the environmental criticality of abiotic raw materials for this reference system. Once again, in this case too, appropriate measures should, if possible, be identified on the basis of indicator values before they have been amalgamated and integrated into a criticality analysis, because there is a high risk of misjudgement otherwise (see also Kosmol et al, 2017).

10.2 Recommendations for application and action

The following recommendations for action are made on the basis of the findings regarding the environmental impacts of raw materials extraction, which have served as examples for investigation, and the assessment results which have been presented:

- Germany depends to a large extent on imports of abiotic raw materials, so a lot of value chains are associated with the negative environmental impacts of mining in other parts of the world. In addition to this, environmental pollution is often unevenly distributed along global value chains: Much of the economic value creation takes place in industrialised countries, where environmental impacts are kept relatively well under control. But the extraction and processing of raw materials often entails huge intrusions into the local environment which would not be tolerated in many industrialised countries. As a consequence, industry and political institutions in Germany and the EU share a burden of ethical responsibility. The environmental impacts of extraction and processing should be taken up in resources policy especially: as a key aim alongside security of supply; and as the basis for the development - in cooperation with industry - of appropriate policy measures, even though this could mean reduced security of supply in the short to medium term.
- In this context, the rating system should also be used to support the governments of resource-rich partner countries in resetting the priorities of their national mining policies in accordance with environmental risks - taking into account the economic, social, geological, and infrastructural basis for decision-making - in order to make progress towards the goal of sustainable development.
- An essential first step in the planning and design of effective measures to be included in an environmental raw materials and resources policy is a reduction in the number of raw materials to be studied. It is recommended that policy measures be focused to start with on raw materials which, from an environmental point of view, on the one hand exhibit a particularly high environmental hazard potential, and on the other hand are of great economic importance to Germany and the EU, i.e. on environmentally critical raw materials. Such

prioritisation is possible using the methodology for raw material related assessment developed in ÖkoRess I. This prioritisation will be applied to more than 50 abiotic raw materials in the follow-up project (ÖkoRess II), which is already under way. Such a prioritisation can also be used by companies in their efforts to establish sustainable supply chain management[68].

- An examination of the extent to which the method developed here can be integrated into current criticality analysis is recommended as a contribution to the scientific and industrial policy debate about critical raw materials. In general, one aim should be for raw material related assessment processes to provide a comprehensive overview of raw material related hazards and impacts. Environmental problems and impacts should be addressed transparently on an equal basis and represented as a separate dimension of assessment. Another reason why a portrayal which is integrated in this way serves a useful purpose is that - against the background of an expected increase in the internalisation of external costs in the mining sector - environmental hazard potentials could, as a result of effective environmental standards, exert considerable influence on the future development of prices and scarcity. This means that environmental hazard potentials are an important additional source of information for the development of a sustainable raw materials policy.
- Finally, the results of raw material related assessments, as they can be expected from the ÖkoRess II follow-up project, facilitate the prioritisation of key areas for research funding, e.g. a raw materials research programme or a technological development programme with a focus on especially environmentally critical raw materials (among other things).

10.3 The need for further research

The authors perceive a continuing need for further research, especially in order to improve the quality and quantity of data available for the application of the method, but also in specific fields in order to improve the tools for assessment, e.g. a description of the standard procedures for the extraction and processing of raw materials, and the establishment of a clear dividing line between processing and smelting, etc.

In addition to this, in the raw material related method of assessment, a final assessment of the "natural environment" level is only possible when a larger number of raw materials has been assessed. As regards the "governance environment" level of assessment, the authors see a need for revision of the indicator, with sufficient attention being given to small-scale mining and the risks associated with it as regards governance in relation to raw materials.

A project covering the application and further development of the methodology of assessment is already under way: ÖkoRess II. A broadening out to include additional applications, and projects which support possible applications at both academic and policy-making levels, is necessary in order to demonstrate the benefits of using the method.

[68] See, for example: BMUB, 2017: Schritt für Schritt zum nachhaltigen Lieferkettenmanagement – Praxisleitfaden für Unternehmen. Internet: www.bmub.bund.de/N54211/

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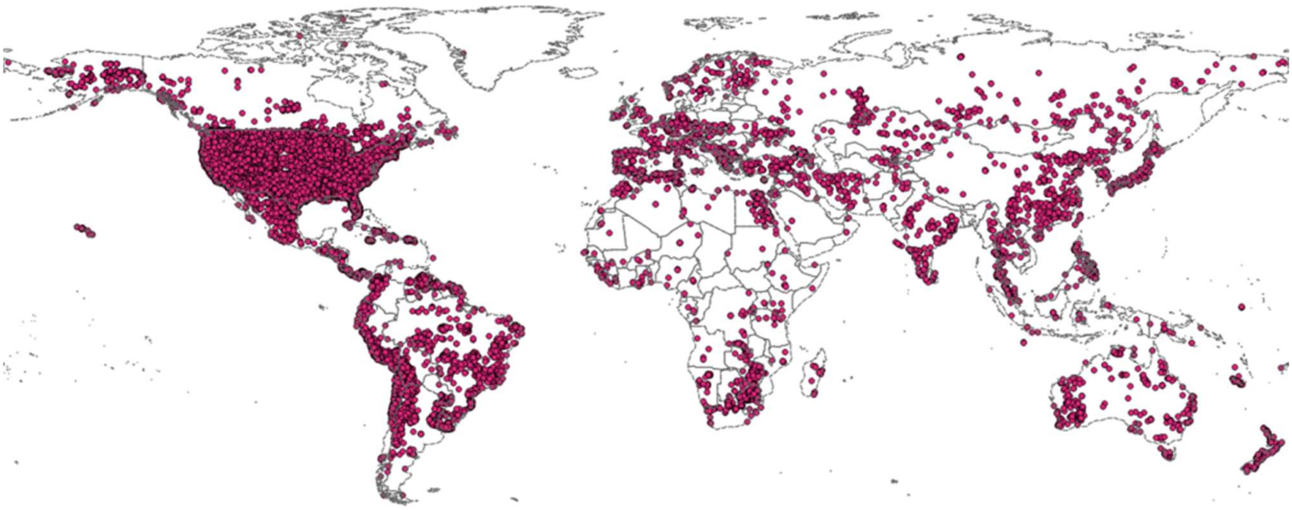
12 Annex

12.1 Geodata from USGS

12.1.1 Mineral Resources Data System - MRDS

The Mineral Resources Data System (MRDS) of the USGS (US Geological Survey) is a collection of data on mines (for the extraction of metals and other raw materials) worldwide. The data is described by the USGS itself as follows: "MRDS is large, complex, and somewhat problematic". The data collection includes a wide range of variables (e.g. name, location, raw material, characteristics of the mine, reserves, etc.). But very few data sets are complete. Each data set contains the following minimum information: the coordinates of the geographical location, the name of the site, and the raw material being extracted. The MRDS data has been collected at various times, so there is considerable variation as regards how up-to-date the data sets are. The USGS describes the current situation as regards maintenance of the database as follows: “As of 2011, USGS has ceased systematic updates to MRDS, and is working to create a new database, focused primarily on the conterminous US. For locations outside the United States, MRDS remains the best collection of reports that USGS has available."

Figure 19 MRDS data (active mines only)



Source of data: USGS; Cartography: ifeu.

Figure 19 provides a spatial overview of the locations of individual mines according to MRDS. Maintenance of the MRDS with its 304,342 data sets is extremely time-consuming and costly, so the USGS has concentrated on US data. Global data sets are required for the spatial analyses in ÖkoRess, however. While a global data set is available through MRDS, much of the data is not very up-to-date, which means that the data is of dubious quality. In addition, no details are provided about the physical extent of the mines or about production capacities. The latter omission means that it is not possible to assess the comparative importance of the individual mines. Moreover, mines located in the USA are over-represented in the data collection. If no adjustment is made, this leads to a skewing of the data for simple frequency distributions.

In addition to the mapping of mining locations worldwide, details of a wide range of raw materials are included, so that it is possible to assess the location of mines for several raw materials. The total number of mines (for each particular raw material) varies considerably, however. This means that samples are not always very representative. Table 26 shows the MRDS data sets for the five raw materials selected for the ÖkoRess I study.

Table 26 Selected raw materials in MRDS

Commodity	Number of mines - RoW	Number of mines - USA
Copper	1,068	4,127
Gold	1,896	12,689
Tungsten (wolfram)	202	1,023
Graphite	141	93
Bauxite	387	393

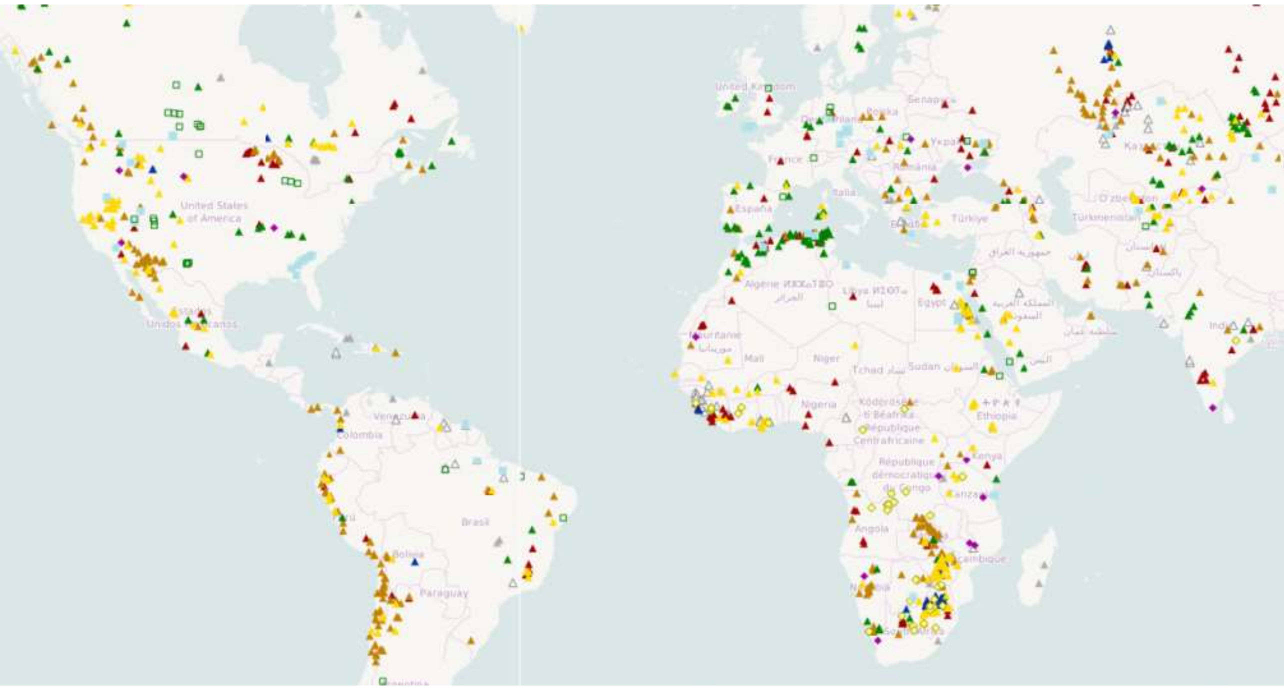
RoW: rest of the world (whole world, excluding the United States)

In preparation for ÖkoRess II, the raw material data sets stored in the MRDS were compared with those of the 51 raw materials in the EU study (EU Commission, 2014). With the exception of gallium, hafnium, magnesium, rhenium, and silicon metal, all the raw materials in the EU study are included in the MRDS.

12.1.2 Major mineral deposits of the world

The data collection is a compilation of data on major deposits throughout the world. The following raw materials were studied: nickel, iron, aluminium, copper, lead and zinc, PGM, gold, rare earths, diamonds, clay, and potash. The aims of the data collection were: to assess the extent of global resources; and to identify the locations of the most important deposits. The spatial data did not have to be especially accurate, because only simple representations of global data were being sought. "The user should expect these point locations to be near the deposits they describe, but the locations may be expected to be one or a few kilometers from the actual locations" (USGS 2005).

Figure 20 Screenshot of the spatial representation of the data set "Major mineral deposits of the world"



Source of data: USGS; Cartography: OpenStreetMap, Http://mrdata.usgs.gov/general/global.html (07.06.2016).

In 2005 the USGS used the data collection and other background reports to publish the 'Reviews of the Geology and Nonfuel Mineral Deposits of the World" in five chapters (Schulz, Briskey 2005). The chapters describe the situation in the USA (Zientek, Orris, 2005), Latin America and Canada (Cunningham et al, 2005), Asia and Oceania (Peters, 2005), Europe and North Central Asia (Nokleberg et al, 2005), and Africa and the Middle East (Taylor et al. 2005).

The data collection does not include any further data on spatial extent, volume of production, or size of deposits.

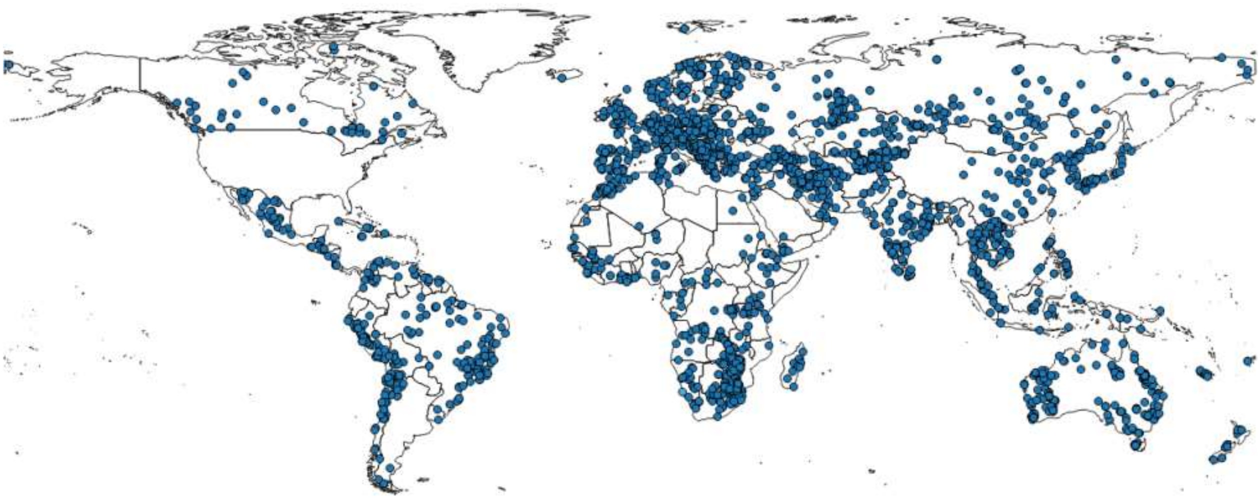
12.1.3 Mineral operations outside the United States

The data set contains spatial data on mines, processing plants, and refineries worldwide, excluding the USA. It is a combination of data from five different studies which were published between 2005 and 2010. In addition to the raw material, details are given of the country, the company, the type of plant, and the volume of production. USGS itself writes: "Data reflect the most recent published table of industry structure for each country." The data set contains data for 6,477 cases (mines) and can be extended to include a data set for the USA.

The studies describe the situation in Latin America and Canada (Bernstein et al, 2006), Asia and Oceania (Baker et al, 2010), North and Central Asia (Baker et al, 2010), Africa and the Middle East (Eros, Candelario-Quintana 2006), and Europe (Almanzar et al, 2010).

In terms of the structure of the data, this data set is the most suitable for assessment in ÖkoRess. However, the data set contains far fewer cases than the MRDS data collection. And, after an initial rough assessment, the spatial data appear to be less accurate than in MRDS. On the other hand, the inclusion of production figures makes this a source of interesting information which is not available in MRDS.

Figure 21 Representation of mineral operations outside the United States (mines only)



Source of data: USGS; Cartography: ifeu.

12.1.4 Additional Geodata from USGS

In addition to the spatial data sets described above, the USGS data platform provides further data sets, some of which have been generated to address more specific questions. Some of these data are of better quality, but they do not meet the key requirements, such as coverage of various raw materials and actual mining locations. They are listed here for the sake of completeness:

- *Mineral deposits of specific types*

- *Volcanogenic massive sulfide deposits*
- *Sediment-hosted zinc-lead deposits*
- *Mississippi Valley-Type and clastic-dominated sediment-hosted lead-zinc deposits*
- *Porphyry copper deposits of the world*
- *Sediment-hosted copper deposits of the world*
- *PGE-Ni-Cr deposit and occurrence bibliographic database*
- *Carbonatites of the world, explored deposits of Nb and REE*
- *Rare earth element mines, deposits, and occurrences*
- *Ni-Co laterite deposits of the world*
- *World phosphate mines, deposits, and occurrences*
- *Podiform chromite deposits*
- *Sediment-hosted gold deposits*
- *Evaporite-related potash resources worldwide*

12.2 Comparison of various methods of data aggregation

Table 27 Portfolio analysis of models for displaying the environmental dimension of the criticality of raw materials

Type of result	Aggregation	Method	Advantages	Disadvantages	Target group	Example	Recommendation
Qualitative	Not aggregated	Traffic lights as risk profile		Cannot be integrated into the existing criticality system			
	Aggregated	When X indicators have a maximum rating	Can be used to a limited extent as an additional dimension of the existing criticality system	Results can only be displayed as less critical, moderately critical, and critical			
		Maximum value principle	Can be used to a limited extent as an additional dimension of the existing criticality system	Only one or a few of the indicators have a crucial impact on the result			

Type of result	Aggregation	Method	Advantages	Disadvantages	Target group	Example	Recommendation
		Ranking/prioritisation “A is more serious than B"	Permits assessment of the importance of the indicators using transparent criteria for the assessment of environmental priority ("environmental hazard" and "distance from the environmental goal"[69])	Not directly applicable: Evaluation criteria need to be developed for ÖkoRess indicators. And quantitative targets (such as 2° target, maximum emission limits, for example) need to be developed for "distance from target".	Science/policy advisors	UBA method for the evaluation of life cycle assessments (UBA 1999)	Fully compliant with ISO DIN DIN 14040/44 (LCA) (DIN 2006a, DIN 2006b); continues to be favoured by UBA

[69] According to UBA (1999), the environmental hazard increases, “in proportion to the seriousness of the potential threat to protected environmental goods in the relevant impact category." The distance from the environmental goal is described as the distance of the current state of the environment in an impact category from a state of environmental sustainability or some other environmental target (e.g. current warming due to climate change compared with the 2° target).

Type of result	Aggregation	Method	Advantages	Disadvantages	Target group	Example	Recommendation
		Standardisation	Permits comparison of indicators which are not causally related against the background of a selected reference system	Typically used for quantitative results; There is no obvious reference system for the ÖkoRess indicators; Might have to be applied to all abiotic raw materials	Science/policy advisors	Environmental impacts of individual aspects compared with total impact in a country (so-called "specific contribution" in life cycle assessment)	Fully compliant with ISO 14040/44 (LCA)
		Decision hierarchy, decision tree, environmental risk analysis: Describe relationships between individual criteria and work out individual combinations of evaluation results for individual criteria	No numerical aggregation is necessary. The result can be traffic lights or a multi-stage classification or a yes/no result for environmentally critical or not	The procedure is very complex, subsequent adjustment of the importance of environmental indicators is not altogether easy	Science/policy advisors		Could be a workable compromise between the desire for scalable results and the rejection of combining apples and oranges
Numerical	Not aggregated	Annotated risk profile		Cannot be integrated into the existing criticality system			
	Partial aggregation at top levels	One of the methods listed below		Cannot be integrated into the existing criticality system			

Type of result	Aggregation	Method	Advantages	Disadvantages	Target group	Example	Recommendation
	Aggregated	Degressive addition	Can be used as an additional dimension of the existing criticality analysis	Single indicator, loss of transparency of partial results, method of calculation cannot be justified scientifically		VDI 4800 Page 2 "Aggregation method for criticality analysis of raw materials" (VDI 2016)	Method adds addends with decreasing value; ensures that high values for criteria are taken into account sufficiently, but do not determine the result on their own
	Aggregated	Summation of ratings	Can be used as an additional dimension of the existing criticality analysis	Single indicator, loss of transparency of partial results			
		Summation of exponential or logarithmic values	Can be used as an additional dimension of the existing criticality analysis High risks are given excessive prominence	Single indicator, loss of transparency of partial results			
		Multiplication of values	Can be used as an additional dimension of the existing criticality analysis A large number of high risks exerts a stronger influence on the results	Single indicator, loss of transparency of partial results			

Type of result	Aggregation	Method	Advantages	Disadvantages	Target group	Example	Recommendation
		With weighting factors for the indicators	Can be used as an additional dimension of the existing criticality analysis	Single indicator, loss of transparency of partial results		Soz. Indikatoren der Uni Augsburg und ökologische Knappheit für Deutschland (Thorenz 2016)	

12.3 Further possible ways of combining the results of the individual indicators by means of numerical aggregation

The main disadvantages of numerical aggregation of the individual results of the indicators for different environmental impacts are:

- The computation or the weighting of the indicators may not have a scientific basis. There is no mathematical relationship between the use of natural space and the pollution hazard potential, for example.

or

- When numerically calculated evaluation results are used, the numerical results usually take on a significance of their own in such a way that the transparency of the individual results is lost and little attention is given to the derivation of the aggregated results according to "subjective" assessments of the importance of the individual indicators.

If a numerical total score is required for further use as a third dimension in the criticality system, the following two methods

- utility analysis with weighting factors set by a body of stakeholders
- and degressive addition

can make it possible to obtain a numerical result with minimum negative side-effects.

12.3.1 Utility analysis

A utility analysis may involve a suitable panel of experts and/or stakeholders using a transparent process to determine the weighting factors for the indicators. This does not resolve the problem that it is essentially impossible to combine individual values which are to all intents and purposes incompatible. Nevertheless it is possible to make it clear that the weighting factors are determined using a social convention which reflects the consensus of participating experts or stakeholders. It is important to prepare for such a process by providing a description - which is both comprehensive and comprehensible - of the objectives and principles of the assessment and to facilitate the process intensively oneself. The better the selection of participants in this weighting process, the greater the number of participants, and the more transparent the process within the group[70], the better one can compensate for the fact that a direct mathematical quantification of the weightings is not possible.

The problem remains that numerical results take on a significance of their own in further discussion. And it is not possible to portray adequately how the limitations - of the way in which the numerical results were generated - were dealt with. This can only be counteracted as far as possible by presenting the results in such a way that the individual results always appear alongside the aggregated results and the limitations of the aggregation method are always made clear explicitly.

Whichever specific method of aggregation is chosen for the numerical aggregation of indicator results, a numerical value must be assigned to each indicator result to make further calculations possible. All the results can be converted to the desired scale, so that only the comparative evaluation rating for each individual indicator is relevant to the final result.

[70] The raw materials advisory council (the multi-project advisory council "Environmental issues of raw materials policy") would be a suitable stakeholder body for suggesting weightings to serve as an example for the assessment within the framework of ÖkoRess II. A selection of UBA staff would be a suitable panel of experts for carrying out the weighting.

The following scores are proposed:

- 1 point: low EHP,
- 3 points: medium EHP,
- 10 points: high EHP[71].

The indicators are grouped together in much the same way as for qualitative combination of the results, with the difference being that the IBCs are now also combined as a group prior to the next stage of the calculation. The influential boundary conditions are entered into the equation as a correcting factor to be applied to the overall result for the environmental goals which has been obtained by addition.

The following groups of environmental goals and IBCs therefore form the basis of the assessment:

- Limitation of destruction of the natural environment
- Reduction of pollution risks
- Prevention of water conflicts
- Influential boundary conditions (IBCs)

First of all, the members of the panel are asked to assign a percentage weighting to each of the individual environmental goals. Each environmental goal should be given a weighting of at least 5%[72]. It is therefore possible to give each environmental goal a weighting between 5% and 90%. The members of the panel need to be given: information about issues, such as the significance of the individual environmental goals; information about the fact that "pollution risks" represents several environmental goals, e.g. human health and protection of ecosystems; and additional information to help with the evaluation. The members of the panel should be given the opportunity to discuss the basis on which they are to make the assessments.

Table 28 Weighting of the environmental goals

Environmental Goals	Range of weighting	Weighting factor to be entered in this column
Limitation of destruction of the natural environment	5% to 90%	
Reduction of pollution risks	5% to 90%	
Prevention of water conflicts	5% to 90%	
Total		100%

The individual indicators of the environmental goals, "limitation of destruction of the natural environment", "reduction of pollution risks", and the ICBs must then be combined using the same procedure to produce the intermediate result for each environmental goal.

[71] In this way, the idea of degressive addition (see section 12.3.2) can also be taken into account to some extent in the utility analysis.

[72] This stipulation may also be discussed and possibly amended by the panel. It is applied here in the example which follows.

Table 29 Weighting of indicators for the environmental goal "limitation of destruction of the natural environment"

Indicators for the environmental goal “natural environment”	Range of weighting	Weighting factor to be entered in this column
4. Method of extraction	5% to 95%	
8. Designated protected areas and AZE sites	5% to 95%	
Total		100%

Table 30 Weighting of the indicators for the environmental goal “prevention of pollution risks”

Indicators for the environmental goal “pollution risks”	Range of weighting	Weighting factor to be entered in this column
1. AMD	5% to 80%	
2. Radioactive substances	5% to 80%	
3. Heavy metals	5% to 80%	
5. Use of auxiliary chemicals	5% to 80%	
6. Risk of naturally induced accidents*	5% to 80%	
Total		100%

* not including the situation in polar regions

No aggregation is necessary for the environmental goal “prevention of water conflicts”, because there is only one relevant indicator.

In theory, the interim results for the individual environmental goals and the preliminary final result using this method lie between 1 (all the results for the individual indicators exhibit a low EHP) and 10 (all the results for the individual indicators exhibit a high EHP).

The ICBs need to be used as a correcting factor, so either they have to be aggregated to produce a single correcting factor in a suitable value range, e.g. 0.5 to 1.5, or each ICB must serve independently as a correcting factor with accordingly low weight (e.g. in a narrower value range from 0.9 to 1.1), depending on the weighting given by the expert panel.

The decision as to how the mathematical implementation is to be carried out does not need to be left to the panel of experts. The panel can also assign a percentage value or values as with the environmental goals. These will then be converted into an appropriate factor or factors.

Table 31 Weighting of the indicators for the influential boundary conditions

Indicators for the ICBs	Range of weighting	Weighting factor to be entered in this column
6a. Polar regions	5% to 85%	
9. Environmental governance	5% to 85%	
10. $CRMD_{global}$	5% to 85%	
11. CED_{global}	5% to 85%	
Total		100%

If it turns out that this specific procedure portrays the actual results inadequately or the results are too spread out, it is not necessary to change the weighting system. A different allocation of points to the EHPs would be sufficient.

12.3.2 Degressive addition

In VDI guideline VDI 4800 degressive addition is recommended for the aggregation of the two dimensions of criticality, i.e. supply risk and vulnerability (VDI 2016). This ensures that high values are properly taken into account, without low values being completely disregarded. Base 3 was selected for the addition, which means that the calculation starts with the indicator with the highest evaluation result as the first addend with one third (0.333). The second highest indicator result is added into the calculation with one third of what remains of the whole (0.222) and so on. This ensures that the desired effect, i.e. that the indicator or indicators with the highest ratings have the greatest influence on the result, is obtained. It is not possible to take account of the size of the differences between the values of the individual indicators. There is a lack of transparency with regard to the influence of the individual indicators on the final result. And, since there is no need for discussion of how the aggregation is set up and carried out, it is also difficult to explain.

VDI 4800 assumes assessment values within the range from 0 to 1 for the evaluation of the individual criteria for supply risk and vulnerability. If a different number of indicators is used, conversion to this value range is advisable. Since this study involves a three-stage assessment, the allocation could be applied as follows, if degressive addition is to be applied:

0.3 = low EHP

0.7 = medium EHP

1.0 = high EHP.

Experience shows that most of the values lie towards the upper end of the theoretically possible range, because - due to the degressive addition - only a few indicators with a high environmental risk potential result in a correspondingly high valuation. The differences between the results of various raw materials are likely to be very low in some cases. In order to counteract this, the degressive addition can be performed using base 4 or 5, which would result in a corresponding broadening of the range of actual results.

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