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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)

Summary

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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)

Summary

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“Everything simple is false. Everything complex is unusable. “

Paul Valéry, lyricist and philosopher, 1871 – 1945

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1 Introduction

The UBA Ufoplan (Environmental Research Programme) project "Discussion of the environmental limits of primary raw material production and development of a method for assessing the environmental availability of raw materials to further develop the criticality concept", ÖkoRess I, has developed a method for assessing the environmental hazard potential of primary extraction of abiotic raw materials. The project and the developed method are intended to support raw material and resource policy in making raw material extraction, raw material supply and raw material use more environmentally sound. In addition, the project will complement scientific and political debate on secure raw material supply, raw material availability and raw material criticality by weighing in with an environmental standpoint on aspects of raw material availability.

For this purpose, a site-related evaluation model was developed first. 40 case studies on mining projects were investigated and an evaluation matrix was developed in an iterative process and tested on the examples. Based on the approach developed, a raw material-related evaluation model was established and applied to the example of five raw materials[1]. In addition to the aspects of supply risk already considered in criticality analyses, the model can be used to compare environmental hazard from the mining industry with vulnerability of the system which utilises raw materials. In an accompanying process, an additional evaluation system was developed for the environmental hazard potential of mining residues[2].

This summary compiles the most important project results. Relevant, extensive project reports have described and published the respective methodological approaches and their derivation comprehensively.

The project advisory council "Environmental aspects of raw material policy", consisting of representatives of environmental, development aid and industrial associations, scientific institutes, social partners and responsible federal institutes, supported the project during its entire duration. Key issues of method development were discussed with the council and individual members in a constructive manner and spirit of trust, which inspired suggestions for further action.

2 Background

The extraction of abiotic primary raw materials such as ores, coal, industrial minerals, natural stones, gravel and sand is always associated with an intervention into the natural environment and in many cases with significant environmental impacts. Depending on the type and character of mining, they lead to a large-scale reshaping of the natural environment, loss of ecosystems, changes in the water balance and pollution of soil, air, groundwater and surface waters. However, if one considers the variety of abiotic raw materials and the mining and processing methods applied, it becomes clear that the environmental impacts vary drastically, in terms of both type and extent.

In the raw material policy debate, however, environmental impacts due to mineral extraction and approaches to improve the situation are also playing an increasingly important role. This is also reflected in the German Federal Government’s resource efficiency programmes ProgRess I and II. It is necessary in this context, in addition to the knowledge of mining-specific environmental problems and potential countermeasures, to raise awareness about the raw materials which are particularly problematic from an environmental standpoint.

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1 These evaluation methods and the study concept will be/have been published in relevant detailed UBA reports https://www.umweltbundesamt.de/umweltfragen-oekoress

2 The partial report "Mining residues" has already been published in the course of the project work: https://www.umweltbundesamt.de/dokument/oekoress-teilbericht-bergbauliche-reststoffe-dr

Numerous individual examples of mining- and raw-material-specific environmental impacts have already been investigated, some of which have been described in great detail. However, a uniform assessment for evaluation purposes is still lacking because of the great variety of abiotic raw materials and the difficulty in quantifying these impacts. Although various raw material-specific evaluation approaches such as toxicological and LCA-based evaluation systems already exist, these are in part limited to individual aspects (e.g. toxicology) and often show considerable weaknesses in terms of data availability or quality.

Environmental aspects for raw material evaluations have also only played a marginal role in the current approaches to estimate supply risks (criticality debate). Although various authors note that environmental and societal consequences of raw material projects already have a significant impact on availability today, it has not been possible to specify these aspects using sufficiently robust raw material-specific data and indicators.

3 Environmental hazard from mining and potential raw material shortages

Like every industrial activity, mining and processing of abiotic primary raw materials are accompanied by environmental impacts. However, in the present conditions there is no method for a comprehensive evaluation of the environmental impacts of mined raw materials. There are considerable methodological and data-related gaps particularly in extraction and processing – those process steps in the production chain that interfere most directly with nature.

The starting point of the project was the theorem that the trend of a steadily increasing raw material extraction within a limited ecosystem will reach its "environmental limits". Physical depletion of deposits is much less of a limiting factor than environmental pollution caused by mining. Environmental limits are to be understood as the carrying capacity of the ecosystem: they are critical stress thresholds meaning that their exceedance results in a hazard of abrupt, drastic and irreversible changes. At a local level, there are many examples in mining where these limits have been exceeded. Disasters such as dam failures and slope failure of waste heaps, often combined with the emission of toxic substances, frequently lead to long-term irreversible damage to ecosystems.

However, impacts by mining that are not due to disaster events but are caused by processes such as landscape destruction and intervention into the groundwater and surface water or soil structure can also lead to relocations of residential areas and require considerable expenditure on rehabilitation and mining industry's so-called eternity tasks (e.g. permanent water management and cleaning). In Germany, the consequences of anthracite coal underground mining in the Ruhr District and lignite open cast mining in Rhineland and Lusatia can be mentioned in this context.

Due to an increasing demand for raw materials, a growing world population and increasing prosperity in many world regions, mining is increasingly penetrating remote and environmentally sensitive areas. In addition, the trend is that fewer and fewer high-grade deposits are being mined. As a result, both extraction costs and the resulting impacts on the environment and local populations will further increase in perspective and the problems described will be exacerbated.

These exceedances of thresholds, often observed locally, cannot be extrapolated to a global scale. The existing global concepts of environmental limits – the 1994 planetary guardrails of the German Government's Scientific Advisory Council on Global Change (WGBU), Rockström's 2009 planetary boundaries – or even global target agreements (e.g. the 2016 Sustainable Development Goals built upon the UN Millennium Targets) fail to provide a starting point for the limits stipulated in the concepts to be disaggregated for mining on a scientific basis. In general, the identification of such thresholds is associated with considerable uncertainties because of the complex biophysical systems and regeneration processes that must be evaluated. This is why the German Advisory Council on the

Environment (SRU) concludes in its 2012 expert report that the precautionary principle must be regularly applied.

Nevertheless, sustainability limits are often not determined on a scientific basis, but rather depend on the acceptance by society or are defined by society itself. The extent to which environmental damage caused by mining is tolerated is a socio-political decision which, among other things, depends on regional culture and the level of prosperity. The extent to which society's acceptance or rejection is expressed in corresponding policy decisions in turn strongly depends on the degree of co-determination by society and governance quality. A policy decision, e.g. for the enforcement of higher environmental standards can lead to an increase in production costs and mining a deposit may become in part or entirely unprofitable. In their entirety, these decisions can reduce the globally available, economically viable quantity of a raw material (reserves) and cause an environment-related induced raw material shortage. In this sense, a link between raw material scarcity and environmental impacts (beyond the local exceedance of thresholds) is to be assumed. However, this is not an absolute physical scarcity caused by resource depletion, but rather an environmentally induced, relative scarcity which can be evaluated by the criticality method.

The evaluation systems have been developed based on these basic ideas and findings. The indicators derived from environmental goals to be explained in the following sections represent the environmental hazard potentials relevant for mining and also take into account the societal environment, first by using a simplified indicator. In addition, connectivity to existing criticality evaluations also had to be taken into account when developing the evaluation systems for a more sustainable raw material supply (cf. Chapter 5).

4 Methods for the evaluation of environmental hazard potentials of primary raw material production

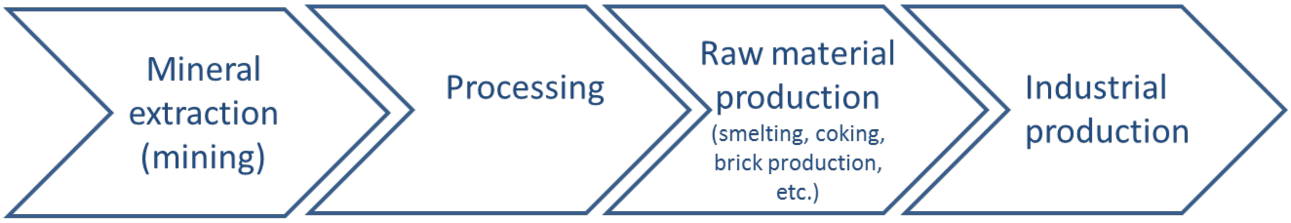
For the (comparative) evaluation of the environmental impact of products, materials, technologies or courses of action, there are evaluation systems such as life-cycle assessment (LCA) or toxicological substance evaluations, which are usually based on concrete examples of exact material flows (material and energy demands) and emissions. Potential environmental impacts are also meticulously evaluated within the Environmental Impact Assessments (EIA) carried out in the framework of individual industrial or mining projects' approval process. However, the evaluation of very complex systems such as the global production of primary raw materials does not facilitate a very detailed approach since relevant data on environmental impacts are not available and their collection would be disproportionately complicated. In addition, there is the fact that ascertained evaluation methods for ecosystem interventions or loss of biodiversity are still lacking. As a result individual sites can (outside a detailed EIA) only be evaluated to a limited extent. Therefore, evaluation methods must firstly be based on facts at a more abstract level and, secondly, be more fundamentally oriented at environmental hazards.

As a consequence, there are limitations to the evaluation methods: exact emissions, propagation conditions and exposure pressures must be omitted just as much as the measures taken in individual cases or the technologies used to prevent or reduce pollutant emissions and to prevent disaster events. The interpretation of the results must therefore take account of the different hazard potentials of the raw materials, which, however, do not necessarily have to lead to corresponding impacts. The results can also be used to identify and implement appropriate measures to prevent such hazard potentials.

The following reference framework has been defined for the developed evaluation methods of the environmental impacts of primary raw material extraction:

- Evaluating the extraction of abiotic raw materials with mining methods.
- The evaluation focuses on the value stages of raw material extraction (mining) and processing. The production of raw materials (smelting, coking, brick production etc.) is included to a limited extent in the raw material- related evaluation.
- The evaluation should also be possible without detailed on-site investigations and should instead be based on generally available data.
- The evaluation considers environmental hazard potentials that are shaped by factors of geology, technology and location.

Figure 1: Generic value chain of mined raw materials and basic materials



Source: Authors' illustration

The approach is characterised by the thought that almost all environmental impacts of mineral extraction and processing are directly related to the following three levels:

- geological preconditions (e.g. geochemical composition of the deposit),
- technical requirements for extraction and processing (e.g. extraction through open pit mining or underground mining, type of processing), and
- site-specific environment (e.g. water availability, local natural accident hazards, sensitivity of the ecosystem concerned).

The developed evaluation systems can be used to evaluate sites and raw materials. For the latter, it should be noted that absolute comparisons between raw materials are not possible due to the limitations described above and the focus on mining extraction and processing. Nevertheless, there is reliability in the sense of a sustainability evaluation and a contribution to the evaluation of supply risks through the connectivity to the criticality concept. Only the basic methodology could be developed, presented and applied as an example within the framework of the project. A final raw material evaluation requires a more comprehensive investigation of further raw materials, which is carried out in the ÖkoRess II follow-up project. The indicator for environmental governance will also be revised as part of ÖkoRess II.

4.1 Site-related evaluation

Firstly, an evaluation approach was developed for site-related evaluation and successively further developed after being applied to 40 case studies of specific mining projects.

This cannot and should not replace the comprehensive and detailed analyses required for the concrete evaluation of environmental impacts in the mining sector such as the consideration of local geological, hydrological and climatic conditions, the evaluation of site sensitivity with respect to the natural environment as well as the taken and planned preventative and remedial measures. However, in the run-up to such very time-consuming and costly environmental impact assessments, decisions regarding planning and financing must be made which require a less complex test scheme that can provide reliable indications of environmental hazard potentials which are possibly very relevant. In principle, the evaluation system is also suitable for showing which technical measures must be taken to counter the hazard potentials. Based on this, benchmarking is also possible at sites with similar hazard conditions.

4.1.1 Method

For the use of the evaluation scheme (Table 1), measurement instructions and – as far as possible – evaluation aids were developed for each indicator. The indicators are evaluated according to the traffic light system: green stands for a low, yellow for a medium and red for a high potential for environmental hazard. An aggregation of the results for the individual indicators is not necessary. A clear presentation of the results per site shows the hotspots of environmental hazard potentials at a glance.

At the **'Geology' level**, the three raw-material-specific indicators

- Precondition for Acid Mine Drainage (AMD)
- Paragenesis with heavy metals and arsenic
- Paragenesis with radioactive substances

describe the most important potentials for relevant environmental problems through the emission of pollutants, which, if necessary, can be roughly assessed without concrete and detailed data from the mining projects with the help of generally available aids (such as the Reuter wheel of metals, the Goldschmidt classification, etc.). For example, the formation of acid seepage water leads to the increased mobilisation of heavy metals. In addition to the particle size and other physical properties of processing residues or overburden promoting AMD, the geochemical preconditions – the presence of sulphidic minerals – are of particular importance.

In addition, deposit-specific indicators such as the size of the deposit and the specific grade indicate the environmental hazard potential as concerns land-take and intervention in ecosystems as a result of the pure mass movement, the size of waste heaps, the extent of the required influence on the water regime and the product-specific demand for energy and auxiliary substances.

Evaluation aids are provided by Petrow's deposit size classification and the specific deposit grades compiled for six raw materials so far within the project.

At the **'Technology' level**, the mining-specific indicator 'Mining method' stands directly for the extent of the intervention at the earth's surface and the associated impacts on biodiversity and landscape. In addition to the raw material-related indicators at the 'Geology level', the processing-specific indicator 'Extraction and processing method' points to further potentials for pollutant emissions. The hazard potential of the pollutants contained in the ore can increase considerably, particularly when the use of toxic auxiliary substances is necessary.

The management-specific indicators 'Mining waste management' and 'Remediation measures' address the special risks of dam failures and tailings ponds, which can be mitigated by safe disposal of residual materials. They also address the question whether renaturation and recultivation should be timely tackled or at least priced in, or whether long-term impairments due to (unavoidable) interventions should be accepted without countermeasures.

The **'Site' (framework conditions)** level concerns 'Natural environment' and 'Social environment'.

The natural environment field considers site-related hazard potential for the environment. This includes, first of all, nature-related aspects which cause increased accident hazards and consequent environmental impacts. A sum indicator comprised of the sub-indicators floods, earthquake, storms and landslides was developed for this purpose. Widely available hazard maps could be identified for each of these indicators, which enable users to carry out evaluations arbitrarily. The only exception is the Arctic region, for which no hazard maps are available. In accordance with the precautionary principle, a general medium hazard potential (evaluation: yellow) was established for natural accident hazards at sites in the Arctic.

Further environmental site indicators were developed for the objectives of 'Avoiding competition in water usage' and 'Protection of valuable ecosystems'. Once more, it was necessary to be able to access to global data. The Water Stress Index proved to be appropriate for the evaluation of potential water scarcity, which however does not adequately depict arid regions since stress is determined as a relative value between supply and extraction. For this reason, additional desert areas were taken into account for the evaluation. An indicator for all environmentally sensitive areas in need of protection would be desirable in order to protect and preserve valuable ecosystems. However, this also requires access to globally available data. In this respect, existing, officially designated protected areas were used as a minimum approach indicator. For example, these include UNESCO's "Natural World Heritage sites" and "Protected Areas" from the IUCN's "Global Protected Areas Programme" (IUCN, International Union for Conservation of Nature). Officially designated protected areas are recorded and publicly available in the World Database on Protected Areas (WDPA). AZE sites designated by the "Alliance for Zero Extinction" (AZE) that showed at least one endangered species were also added.

This means that all environmental site indicators can be evaluated using global maps. A GIS evaluation system was also developed within the framework of the project with a view to the transition to raw material-related evaluation.

In the 'Conflict potential with local population' indicator, which uses two Worldwide Governance Indicators of the World Bank, the 'Social environment' field considers whether

- the population groups affected by environmental impacts can formulate their concerns into political discourse without fear of reprisal;
- the implementation of political decisions is not systematically undermined by corruption.

It is assumed that in situations where these conditions prevail, the establishment and control of effective environmental standards is more likely than in regions with poorer governance so that the general conflict potential triggered by environmental impacts from the mining industry is minimised. It is also assumed that good governance is more likely to lead to a peaceful resolution of the conflict in the event of negative environmental impacts and the resulting disadvantages for the local population.

Table 1: Evaluation scheme for environmental impacts from mining for individual mining examples

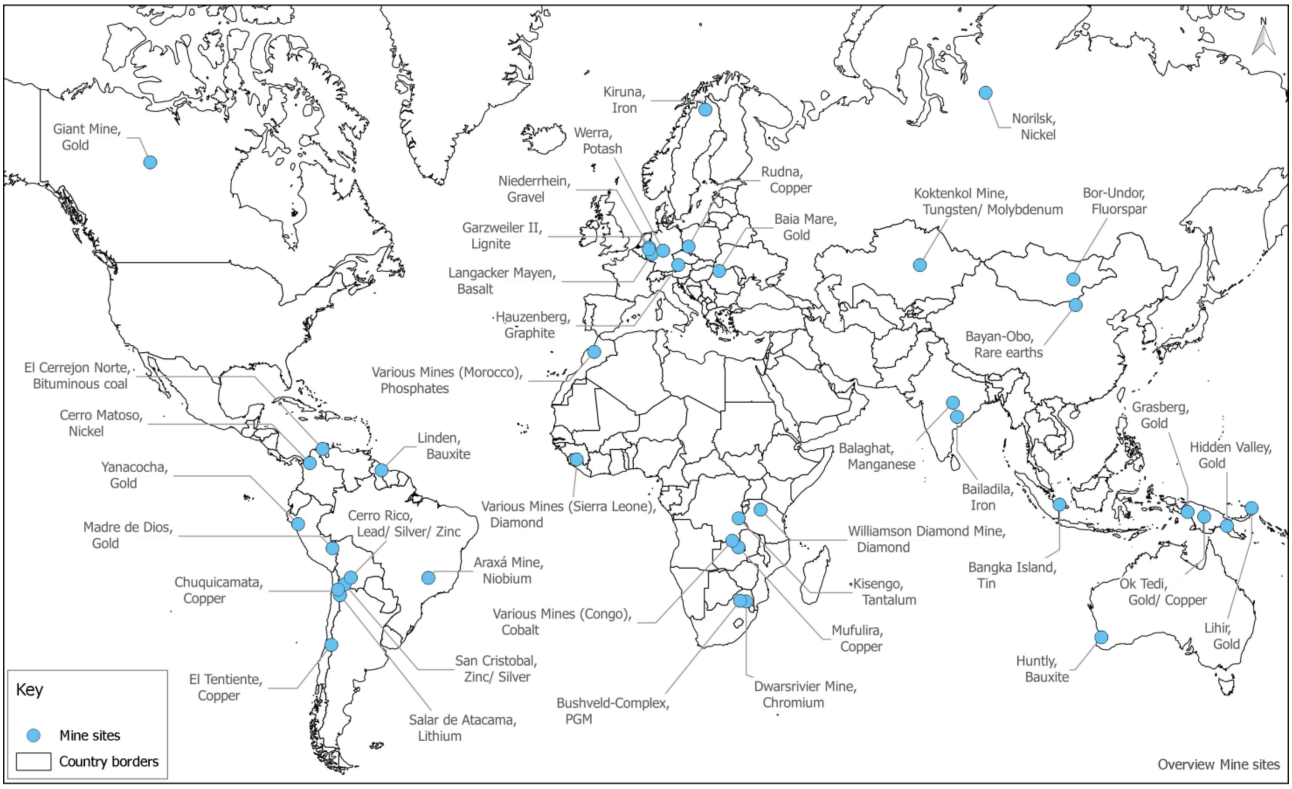
	Field	Goal	Indicator	Evaluation of environmental hazard potential (EHP)		
				Low	Medium	High
Geology	Commodity-specific	Avoiding pollution risks	Preconditions for acid mine drainage (AMD)	Geochemical preconditions for AMD do not exist	Geochemical preconditions for AMD exist in part	Geochemical preconditions for AMD exist
			Paragenesis with heavy metals	The deposit has no elevated heavy metal concentrations	The deposit has slightly elevated heavy metal concentrations	The deposit has strongly elevated heavy metal concentrations
			Paragenesis with radioactive components	The deposit has low uranium and/or thorium concentrations	The deposit has slightly elevated uranium and/or thorium concentrations	The deposit has elevated uranium and/or thorium concentrations
	Deposit-specific	Limiting the direct impacts on ecosystems	Deposit size	Small	Medium	Large
		Limiting the effort for exploitation	Specific grade	Rich	Medium	Poor
Technology	Mining-specific	Limiting the direct impacts on ecosystems	Mining method	Underground mining	Solid rock open pit mining	Alluvial or unconsolidated sediment mining
	Processing-specific	Avoiding pollution risks	Extraction and processing method	Without auxiliary substances	With auxiliary substances	With toxic substances
	Management-specific	Minimisation of risks from mining waste	Mining waste management	Safe storage / deposition of tailings in the deposit	Among others, stable waste heaps, marketing of mine residues	Risky deposition, unstable tailing-ponds, no tailings management system
		Minimisation of longevity of impacts	Remediation measures	Process-parallel rehabilitation	Financial accruals for rehabilitation	No provisions
Site (framework conditions)	Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquake, storms, landslides	All sub-indicators show a low accident hazard (green)	At least one sub-indicator shows a medium accident hazard (yellow), none a high*	At least one sub-indicator shows a high accident hazard (red)
		Avoiding competition in water usage	Water Stress Index (WSI) and desert areas	Low water stress	Moderate water stress	Heavy water stress or desert region
		Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	AZE site or "protected area" (e.g. IUCN Cat. V-VI, national reserve)	"Highly protected area" (e.g. World Heritage Site, IUCN Cat. I-IV)
	Social environment	Avoiding environment-related conflicts in resource usage	Conflict potential with local population *(2 Worldwide Governance Indicators)*	Democratic rights existing; sound corruption control *(indicator values for 'Voice and Accountability' and 'Corruption Control' >65%)*	Moderate democratic rights and/or corruption control *(indicator values >45% <65%)*	Poor democratic rights and/or corruption control *(indicator values <45%)*

* Natural accident hazards for the Arctic are generally evaluated with yellow (medium potential) in the lack of hazards maps

4.1.2 Application of the method using the example of selected case studies

40 case studies about mine sites were used for the purpose of testing and further methodologic development. Those cases were selected that represented a broad spectrum of different raw materials (e.g. aluminium, lead, copper, cobalt, rare earths, iron, diamond, graphite and coal), regions (see Figure 2), mining technologies, environmental problems and natural accident hazards. The investigation included eight case studies about gold to see what effect different framework conditions may have on the evaluation of the same raw material. The description of the case studies has shown that there are frequently considerable gaps in data availability. Therefore, evaluation tools have gradually been further developed in such a way that an evaluation based on knowledge of the exact position of the projects, the geological site conditions and the planned extraction and processing technology is now also possible (cf. Section 4.1.1). In addition, an evaluation of the data quality for each case study and indicator was given.

Figure 2: Location and raw materials extracted in the 40 case studies



The evaluations indicate that mining or geological expertise is of great advantage in evaluating the case studies, but scientists of other fields also can carry out the evaluation. Research and evaluation should preferably be done by one and the same person. The results also show a good spread with respect to the assigned ratings for the indicators. More than 70% of the indicators were never given the same rating in any of the case studies. There was only one case study where no indicator was evaluated as 'green', and three with no 'red' indicator.

Table 2 shows the evaluation results for selected case studies.

Table 2: Application of the site-related evaluation method using the example of selected case studies

Country	Tanzania	Mongolia	Peru	Papua New Guinea	Chile	DR Congo
Region	Mwadui	Bor-Undor	Madre de Dios	Hidden Valley	El Teniente	Kisengo
Raw material	Diamond	Fluorspar	Gold	Gold	Copper	Tantalum
Conditions for Acid Mine Drainage (AMD)	B2	A	B1	B2	A	B1
Paragenesis with heavy metals	B2	A	B2	B2	A	B1
Paragenesis with radioactive components	B2	A	B2	B2	B2	B2
Deposit size	A	A	B1	A	A	A
Specific grade	B1	Z	A	A	A	A
Extraction method	A	A	A	B1	A	A
Use of auxiliary materials	A	A	A	A	A	A
Tailings management	A	A	A	A	Y	B2
Remediation measures	A	B1	A	A	Y	A
Incident hazard	A	A	A	A	A	A
Water Stress Index (WSI) and desert areas	A	A	A	A	A	A
Certified protected areas and AZE sites	A	A	A	A	A	A
Conflict potential with local population	A	A	A	A	A	A

Low EHP	Medium EHP	High EHP

Data quality:

A = High: directly derived from available data
B1 = Medium: estimated based on available information
B2 = Medium: rated according to measurement instructions
C = Low: no specific information, no blanket stipulations by the measurement instructions, (expert) estimate
Y = Evaluation is not possible at the site because of missing data since neither data for an estimation nor blanket evaluation rules are available.
Z = Evaluation is not possible because of (still) missing methodological principles or comparative data.

4.2 Raw material-related evaluation

In order to enable a raw material-related evaluation, the findings from the site-related method were transferred to the global extraction of raw materials.

4.2.1 Method

To take account of the global scale of environmental hazard potentials, the evaluation refers to the respective global total production of a raw material.

The initial situation of geological conditions (‘Geology’ level) in particular is mostly comparable for deposits of the same raw material. This can be chiefly attributed to the fact that similar conditions and enrichment processes were often predominant in the genesis of deposits of the same raw material. Amongst others, such an observation allows a conclusion about whether a deposit type of a specific raw material has high or low heavy metal and sulphide concentration. If the characteristic concentrations are in the high range, the relevant environmental hazard potentials are estimated as high.

Comparable considerations can also be made about technical necessities (‘Technology’ level). Together with the generally prevailing economic conditions (cost pressure) and the global distribution of mining machinery and processes, this leads to the situation that comparable deposits are developed and exploited worldwide using similar technological processes. In this respect, fairly general raw material-based conclusions can be drawn. It is relevant for an environmental evaluation that some of these characteristics also provide information about potential environmental problems, which can be illustrated by the following example: If large quantities of chemicals are used for the processing of a mineral, there is in principle a risk that it may leak into the environment. Considering the global mineral and raw material production and the number of deposits and mining projects, the likelihood that such chemicals will not be properly managed and there will be environmental pollution must not be ignored. Given such technical characteristics, low, medium and high environmental hazard potentials are attributed to various raw materials.

The third evaluation level (‘Natural environment’ level) relates to site-related characteristics. The starting point for the site-related evaluation was that certain environmental impacts strongly depend on local conditions. For example, accident hazards caused by natural disasters are particularly likely in regions strongly threatened by floods, earthquakes, storms and landslides. This starting point also applies to the transfer to the raw material-related evaluation scheme, except that instead of evaluating a single site, all the mining sites of the raw material must be evaluated world-wide. In the case of an ideal data situation, i.e. if georeferenced data on mine site locations for abiotic raw materials including their production volume are available, geodata evaluation developed for each raw material can be used to reliably determine the global situation of environmental hazard. The MRDS database from the USGS can be identified as the best database widely available. Due to the lack of mine-specific production volume data, an approximation methodology has been developed which can be used to make robust estimates for the example of the five raw materials investigated. Robustness depends on the number of available cases in the MRDS database. The final assessment of the results from geodata evaluation i.e. defining the thresholds "from which part of the global production, e.g. in areas affected by natural accident hazard, is the environmental hazard potential small, medium or high" has not yet been carried out. This requires a much broader total population of investigated raw materials, which will be dealt with in the follow-up ÖkoRess II project.

It should be noted for all three levels described above that the evaluation approach deliberately excludes the actual management and possible countermeasures to avoid harmful environmental consequences. This is not to imply that such measures would be ineffective. However, it must be assumed from a global perspective that risk mitigation measures are not or only insufficiently implemented in many projects and regions for reasons such as cost pressure or governance problems. To make a rough estimate about the extent to which there is compliance with effective environmental protection standards, a general assumption has been made at the fourth evaluation level 'Governance environment' that countries with good governance in particular take effective environmental protection measures. Though mining companies can implement high standards (e.g. on a voluntary basis) even under poor governance conditions, they have many options to not or only partially implement standards to save operating costs.

As a fifth evaluation level, indicators were added to the mineral / raw material value chain in the evaluation scheme. The global scale of environmental hazard potentials, including raw material production (smelting), has been estimated using the indicator of cumulative raw material demand for global production (CRD_{global}). In addition, the total global primary energy demand (CED_{global}), including raw material production, has also been taken into account.

Ultimately, the approach endeavours to establish qualified estimates about the environmental hazard potential (EHP) of mining and processing a given raw material. In doing so it uses a combination of different indicators and a rough evaluation scheme – low / medium / high environmental hazard potential (EHP).

Table 3 shows the developed evaluation scheme.

Table 3: Evaluation scheme for raw material-related environmental hazard potential (EHP)

	Goal	Indicator	Evaluation of environmental hazard potential (EHP)		
			Low	Medium	High
Geology	Avoiding pollution risks	1. Preconditions for acid mine drainage (AMD)	Geochemical preconditions for AMD do not exist	Geochemical preconditions for AMD exist in part	Geochemical preconditions for AMD exist
		2. Paragenesis with heavy metals	The deposits usually have no elevated heavy metal concentrations	The deposits usually have slightly elevated heavy metal concentrations	The deposits usually have strongly elevated heavy metal concentrations
		3. Paragenesis with radioactive substances	The deposits usually have low uranium and/or thorium concentrations	The deposits usually have slightly elevated uranium and/or thorium concentrations	The deposits usually have elevated uranium and/or thorium concentrations
Technology	Limiting the direct impacts on ecosystems	4. Mining method	Commonly extracted in underground mines	Commonly extracted from solid rock open pit mines	Commonly extracted from alluvial or unconsolidated sediment mines and/or dredging in rivers
	Avoiding pollutant risks	5. Use of auxiliary substances	Standard extraction and processing methods without auxiliary chemicals	Standard extraction and processing methods using auxiliary chemicals	Standard extraction and processing methods using toxic reagents and auxiliary substances
Natural environment	Avoiding natural accident hazards	6. Accident hazards due to floods, earthquake, storms, landslides	Limits to medium and high EHP are not exceeded	> X% of current extraction in areas with medium natural accident hazard	> Y% of current extraction in areas with high natural accident hazard
	Avoiding competition in water usage	7. Water Stress Index, WSI and desert areas	Limits to medium and high EHP are not exceeded	> X% of current extraction in areas with moderate water stress	> Y% of current extraction in areas with heavy water stress or in desert regions
	Protection of valuable ecosystems	8. Protected areas and AZE sites	Limits to medium and high EHP are not exceeded	> X% of current extraction in 'protected areas' or AZE sites	> Y% of current extraction in 'highly protected areas'
Governance environment	Compliance with standards	9. Environmental governance in major production countries	In the three leading production countries, none of the WGI indicators, Voice & Accountability and Control of Corruption, fall below 50%	In the three leading production countries, none of the WGI indicators, Voice & Accountability and Control of Corruption, fall below 25 %	In the three leading production countries, at least one of the WGI indicators, Voice & Accountability and Control of Corruption, falls below 25 %
Value chain	Limiting the global extent of EHPs	10. Cumulated raw material demand of global production (CRD_{global})	CRD_{global} < 16.5 million t per year	CRD_{global} 16.5 -200 million t per year	CRD_{global} > 200 million t per year
	Limiting the global extent of EHPs	11. Cumulated 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

4.2.2 Application of the method using the example of five selected raw materials

Five raw materials (copper, gold, aluminium, tungsten and graphite) were evaluated in an example using provisional evaluation limits. The results are summarised in Table 4 and Table 5. It should be noted that the thresholds for indicators 6, 7, 8, 10 and 11 have not yet been finally specified. The reason is that a specification ultimately derived from a comparative evaluation of different raw materials requires the consideration of a sufficiently large population of raw materials. This will only be carried out within the follow-up project[3]. The same applies to Indicator 9 (Environmental governance), which will also be redefined within the follow-up project.

[3] The follow-up project "Further development of management options for an environmental raw material policy (ÖkoRess II)" is being carried out by Öko-Institut, ifeu, Projekt Consult and adelphi commissioned by the German Environment Agency.

Table 4: Results of raw material-related evaluation of the environmental hazard potential (EHP) using the example of copper and gold

Indicator		Copper			Gold		
		B	Explanation	Q	B	Explanation	Q
1	Conditions for acid mine drainage (AMD)		According to the Goldschmidt classification, copper is a chalcophilic (S-loving) element and mostly available as a sulphide.	+		According to the Goldschmidt classification, gold is a siderophilic element and available both as a sulphide and an oxide.	o
2	Paragenesis with heavy metals		Copper itself exhibits toxic properties and is specified in the present method description as a heavy metal.	+		Gold is a precious metal and non-toxic. But it is often in paragenesis with heavy metals in deposits (e.g. in Cu-Au ores).	o
3	Paragenesis with radioactive components		No systematic data on the paragenesis of Cu with uranium and thorium in minable deposits. Data of Chinese Cu deposits show low contamination but are not sufficient for evaluation because of a limited world market share. Rating according to recommendation for metals.	-		Gold from underground mining in South Africa (approx. 7.5% of global production) is in paragenesis with high uranium concentrations.	o
4	Mining method		Hard rock open cast mining from massive mineralisations such as subduction zones along the 'ring of fire' (copper porphyries) is the standard copper mining method.	+		Hard rock open cast mining from massive ore deposits is the standard mining method (stock works, porphyries).	+
5	Use of auxiliary materials		Flotation combined with solvent extraction is the standard processing method.	o		Large mines employ cyanide leaching for processing; small mines use amalgamation.	+
6	Avoiding natural incident hazard		Weighted mean evaluation result (58%) exceeds the average for the five raw materials (33%).	-		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-
7	Avoiding competition in water usage		Weighted distribution result for high hazard potential (54%) exceeds the average for the five raw materials (30%).	-		Weighted distribution result for high hazard potential (41%) exceeds the average for the five raw materials (30%).	-
8	Protection of valuable ecosystems		Weighted distribution result for high hazard potential (6%) exceeds the average for the five raw materials (2%).	-		Weighted distribution result for high hazard potential (4%) exceeds the average for the five raw materials (2%).	-
9	Environment governance in the most important production countries		The three major copper producers are Chile, China and Peru with global shares of 31.1%, 9.5% and 7.5%. V&A: 80.30%, 5.42% and 51.23%. CoC: 90.87%, 47.12% and 32.69%. One IV is below 25%.	+		The three major gold producers are China, Australia and Russia with global shares of 15.1%, 9.2% and 8.3%. V&A: 5.42%, 93.6% and 20.2%. CoC: 47.12%, 95.19 and 19.71%. Three IVs are below 25%.	+
10	CRD$_{global}$		Copper CRD: 128,085 kg/t; jPP: 18,700,000 t; CRD$_{global}$ just under 2.4 billion t.	+		Gold CRD: 740,317,694 kg/t; jPP: 3,000 t; CRD$_{global}$ approx. 2.4 billion t.	+
11	CED$_{global}$		Copper CED: 50,700 MJ/t; CED$_{global}$ just above 1 million TJ/a.	+		Gold CED: 208,000,000 MJ/t, CED$_{global}$ 624,000 TJ/a.	+

Table 4 und Table 5 use the following abbreviations:

E = Evaluation
- Red = high environmental hazard potential (EHP)
- Yellow = medium EHP
- Green = low EHP

Q = Data quality
- + = high
- o = medium
- - = low

V&A = WG indicator Voice & Accountability based on 2014 data

CoC = WG indicator Control of Corruption based on 2014 data

IV = Indicator value

CRD = Cumulated raw material demand according to Giegrich et al. (2012)

CRD$_{global}$ = Cumulated raw material demand of global production

CED = Cumulated energy demand according to Nuss & Eckelmann (2014), for graphite according to Giegrich et al. (2012)

CED$_{global}$ = Cumulated energy demand of global production, also total primary energy used for global raw material production

aPP = Annual primary production in 2015 according to USGS (2016)

WG indicator = World Governance Indicator

Table 5: Results of raw material-related evaluation of the environmental hazard potential (EHP) using the example of aluminium, tungsten and graphite

Indicator		Aluminium			Tungsten			Graphite		
		E	Explanation	Q	E	Explanation	Q	E	Explanation	Q
1	Conditions for acid mine drainage (AMD)		According to the Goldschmidt classification, aluminium is a lithophilic element and is usually available as an oxide.	+		According to the Goldschmidt classification, tungsten is a siderophilic (S-loving) element and available both as a sulphide and an oxide.	o		Graphite is not usually avalaible as a sulphide.	o
2	Paragenesis with heavy metals		Aluminium is not a heavy metal. According to the evaluation method for metals, the evaluation applies '1'.	o		Tungsten is not considered a toxic heavy metal. According to the evaluation method for metals, the evaluation applies '1'.	o		Graphite is an abiotic non-metallic raw material. The evaluation must be adjusted in the case of references to paragenesis with heavy metals.	-
3	Paragenesis with radioactive components		Average data on Chinese bauxite deposits (16.3% of global production) suggests that aluminium often is in paragenesis with uranium and/or thorium of slightly elevated concentrations.	o		No specific data is available. In accordance with the procedure described in Section 4.1.3, the evaluation applies '1'.	-		Graphite is not available in paragenesis with radioactive components.	o
4	Mining method		Bauxite is mined from tropical weathering horizons, which are close to the surface, therefore lose rock open cast mining technology is needed.	+		Tungsten is mined as tungstenite or scheelite in underground mining. Since the deposits usually are small-scale lode or metasomatic deposits, they require selective extraction.			Graphite is mined in underground mining. Since the deposits usually are lode deposits, they require selective extraction.	o
5	Use of auxiliary materials		Leaching and thermal treatment in a rotary kiln lead to an evaluation of 2.	+		Tungsten ores are processed using gravimetric methods and heavy suspension separation. Refining using indirect flotation (flotation of the contaminating accompanying minerals) rarely takes place.	o		Graphite is usually processed using flotation and auxiliary chemicals.	o
6	Avoiding natural incident risks		Weighted distribution result for medium hazard potential (37.2%) just exceeds the average for the five raw materials (37.1%).	-		Weighted distribution result for medium hazard potential (72%) exceeds the average for the five raw materials (37%).	-		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-
7	Avoiding competition in water usage		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-		Weighted distribution result high hazard potential (35%) exceeds the average for the fiver raw materials (30%).	-
8	Protection of valuable ecosystems		Weighted distribution result for medium hazard potential (5%) exceeds the average for the five raw materials (3%).	-		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-		Weighted distribution results for medium and high hazard potential are below the average for the five raw materials.	-
9	Environment governance in the most important production countries		The three major aluminium producers are Australia, China und Brazil with global shares of 32.1%, 22.4% and 14.2%. V&A: 93.60%, 5.42% and 60.59%. CoC: 95.19%, 47.12% and 44.23%. One IV is below 25%.	+		The three major tungsten producers are China, Vietnam and Portugal with global shares of 81.8%, 4.6% and 3.2%. V&A: 5.42%, 9.85% and 83.25%. CoC: 47.12%, 37.5 and 79.33%. Two IVs are below 25%.	+		The three major graphite producers are China, India and Brazil with global shares of 65.6%, 14.3% and 6.7%. V&A: 5.42%, 61.08% and 60.59%. CoC: 47.12%, 38.94 and 44.23%. One IV is below 25%.	+
10	CRD_{global}		Aluminium CRD: 10,412 kg/t; aPP: 58,300,000 t; CRD_{global} approx. 607 million t	+		Tungsten CRD: 343,423 kg/t; aPP: 87,000 t; CRD_{global} just under 30 million t	+		Graphite CRD: 1,066 kg/t; aPP 1,190,000 t; KRA_{global} ca. 1.2 million t	+
11	CED_{global}		Aluminium CED: 131,000 MJ/t; CED_{global} approx. 7.6 million TJ/a	+		Wolfram CED: 133,000 MJ/t; CED_{global} 11,571 TJ/a	+		Graphite CED: 437 MJ/t; CED_{global} 520 TJ/a	+

4.2.3 Combining the individual results

After discussing and checking numerous aggregation methods, the authors recommend combining the individual results as a qualitative evaluation of the hazard potential reasoned verbally-argumentatively. For this purpose, a classification of the total environmental hazard potential into the low – medium – high levels is carried out analogously to the individual indicators. As a supplement, a ranking is performed among the raw materials that are assigned to the same stage[4].

As a basis for the combination of the individual results from the evaluation of the indicators, the indicators are first clustered into environmental goals and influencing boundary conditions (iBC). In addition, a hierarchy is developed for the environmental goals according to their environmental significance taking into account the environmental hazard and the distance to environmental target. Table 6 shows the result of the indicators thus grouped.

Table 6: Grouping indicators by key environmental goals and as influencing boundary conditions

Environmental goals	Indicators
Very high environmental significance	
Limiting the direct impacts on ecosystems and protection of valuable ecosystems (short: Ecosystems)	No. 4 Mining methods No. 8 Protected areas and AZE sites
High environmental significance	
Avoiding pollution risks and their spread by natural accident hazards (short: Pollution risks)	No. 1 Preconditions for Acid Mine Drainage No. 2 Paragenesis with heavy metals No. 3 Paragenesis with radioactive substances No. 5 Use of auxiliary materials No. 6 Accident hazards due to floods, earthquake, storms, landslides
Avoiding competition in water usage (short: Water)	No. 7 Water Stress Index (WSI) and desert areas
Influencing boundary conditions (iBC)	**Indicators**
Position in the Arctic region (short: Arctic)	No. 6 Special rule on Arctic regions
Compliance with standards (short: Environmental governance)	No. 9 Environmental governance in major production countries
Global extent of EHP (short: CRD_{global})	No. 10 Cumulated raw material demand of global production *
Global extent of EHP (short: CED_{global})	No. 11 Cumulated energy demand of global raw material production

4 If, however, a numerical aggregation should be carried out, it is important to develop a transparent method and to have the weighting of indicators carried out by a panel of experts and stakeholders as a societal convention. In addition to a detailed description of the qualitative combining evaluation, the (as yet unpublished) report "Evaluation of environmental hazard potentials for primary production of abiotic raw materials – A method for a raw material-related approach" contains a brief outlook of the requirements for a potential numerical model (see sources in Footnote 1). Cf. https://www.umweltbundesamt.de/umweltfragen-oekoress

The individual indicators are first combined within the environmental goals and for the iBCs according to concrete evaluation rules which thus provide interim results. The preliminary total environmental hazard potential is then determined by combining the results of the individual environmental goals, which is then fine-tuned to obtain the total environmental hazard potential for each raw material where iBCs are taken into account if necessary (Table 7).

Table 7: Merger of the evaluation results for environmental goals on tEHP using the example of the evaluation of the five investigated raw materials.

Raw materials	Copper	Gold	Aluminium	Tungsten	Graphite
Environmental goals	**Environmental hazard potential (EHP)**				
Very high env. significance					
Ecosystems	High	High	High	Low	Low
High env. significance					
Pollution risks	High	High	Medium	Medium	Low
Water	High	High	Low	Low	High
	Preliminary total environmental hazard potential (ptEHP)				
Preliminary result environmental goals	**High**	**High**	**High**	**Low**	**Medium**
	Copper	**Gold**	**Aluminium**	**Tungsten**	**Graphite**
iBC	**Environmental hazard potential (EHP)**				
Arctic	Medium	Medium	Low	Low	Low
Environmental governance	High	High	High	High	High
CRD_{global}	High	High	High	Medium	Low
CED_{global}	High	High	High	Medium	Low
Evaluation result iBC	High	High	High	Medium	Low
	Total environmental hazard potential (tEHP)				
Total result	**High**	**High**	**High**	**Low**	**Medium**

* Evaluation still preliminary

Subsequently, the ranking of the raw materials that were classified as equal in the context of total environmental hazard potential takes place. Accordingly, the provisional result of the evaluation example for the five raw materials is:

High tEHP	Rank 1: copper and gold
	Rank 3: aluminium
Medium tEHP	Rank 1: graphite
Low tEHP	Rank 1: tungsten.

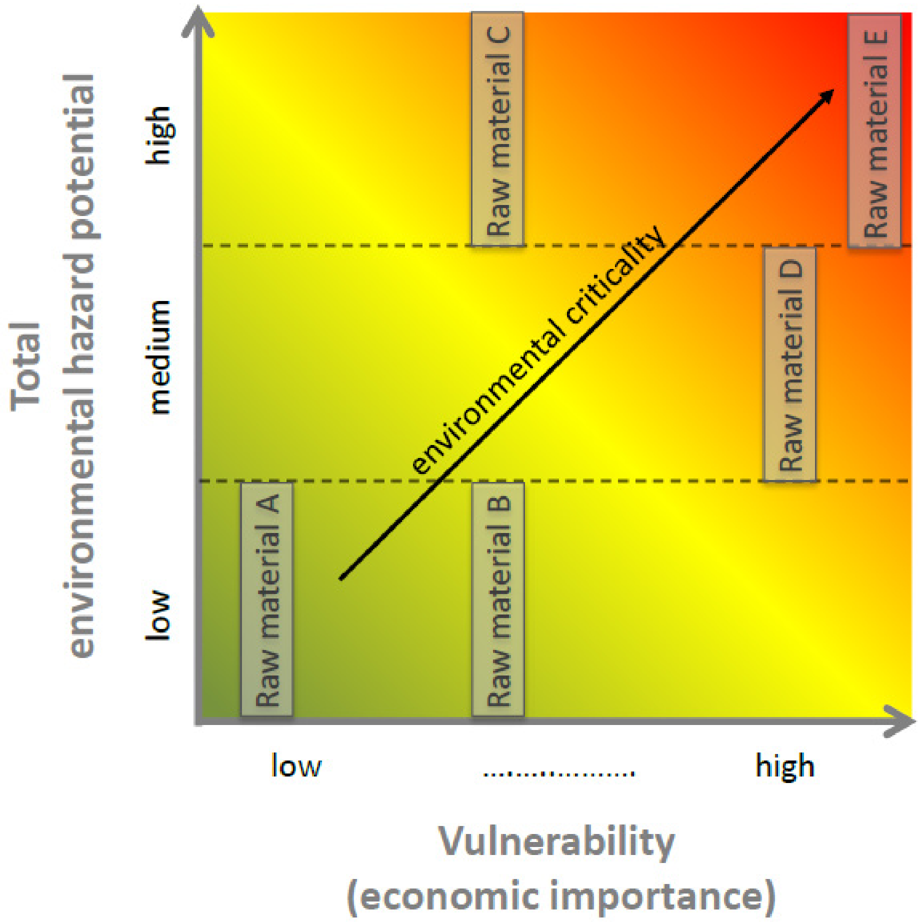
5 Integrating the results into the existing concepts of raw material criticality

The results of the raw material-related evaluation should be compatible with the existing criticality concepts so that the environmental aspects in the current discussion on the criticality of raw materials can take better effect. The discussion about criticality emerged mainly from the concern that price increases, strong price fluctuations and shortages could lead to supply risks in the near and medium term. Because many industrialised countries depend on imports, such issues could endanger the economic and industrial development of companies, technologies and regions in those countries. Environmental aspects have only been taken into account to a certain extent so far, namely by means of 'Environmental indicators' in the *'Supply risk'* dimension or as a separate, third, *'Environment'* dimension. This project has issued the clear recommendation not to assign environmental hazard potentials to the supply security axis, but instead to integrate it into the concept as an independent third environmental dimension. It is fundamentally important to present the raw material-related environmental hazard potentials in a transparent and autonomous manner, and independently of an economic evaluation such as the conventional criticality evaluation.

Based on the plausible assumption that the future will bring an increased internalisation of external costs through more effective voluntary or mandatory environmental standards in the global mining sector, environmental hazard potentials will also present real economic supply risks (in the future). Increased production costs due to more effective environmental standards can lead to a reduction in the profitably minable raw material quantities (reserves) and thus to a shortage and a subsequent price increase. In this sense, the identified environmental hazard potentials form an environmentally limited raw material availability which, taken together with the vulnerability of the reference system using raw materials, results in environmental criticality. It can provide politics and enterprises with robust support for sustainable extraction, supply and use of raw materials. In response to high environmental criticality, certain measures known from the previous criticality discussion are possible, for example material saving, ecodesign and recycling. On the other hand, substitution is only reasonable if a raw material is replaced with a less polluting alternative. In addition to purely material substitutions (replacement of a raw material by another), functional substitutions are also possible (other technical and/or systemic approaches for providing the same function). Substitution decisions must take account of the environmental impacts of the considered alternatives and compare them over their entire life cycle (including the products made therefrom), which the method presented here cannot perform. In addition, the environmental criticality agenda's portfolio of measures should consider a key issue: high environmental criticality must not lead to selected sourcing of the raw materials concerned. In light of global responsibility, global justice (polluter pays principle) and corporate responsibility, it should instead give rise to the implementation of sustainable environmental standards.

Figure 3 shows an example of how the results of the environmental hazard potential can be presented in relation to the vulnerability of the investigated raw materials.

Figure 3: Sample illustration of environmental hazard potential versus vulnerability and environmental criticality



Source: Authors' illustration based on Kosmol et al. (2017)

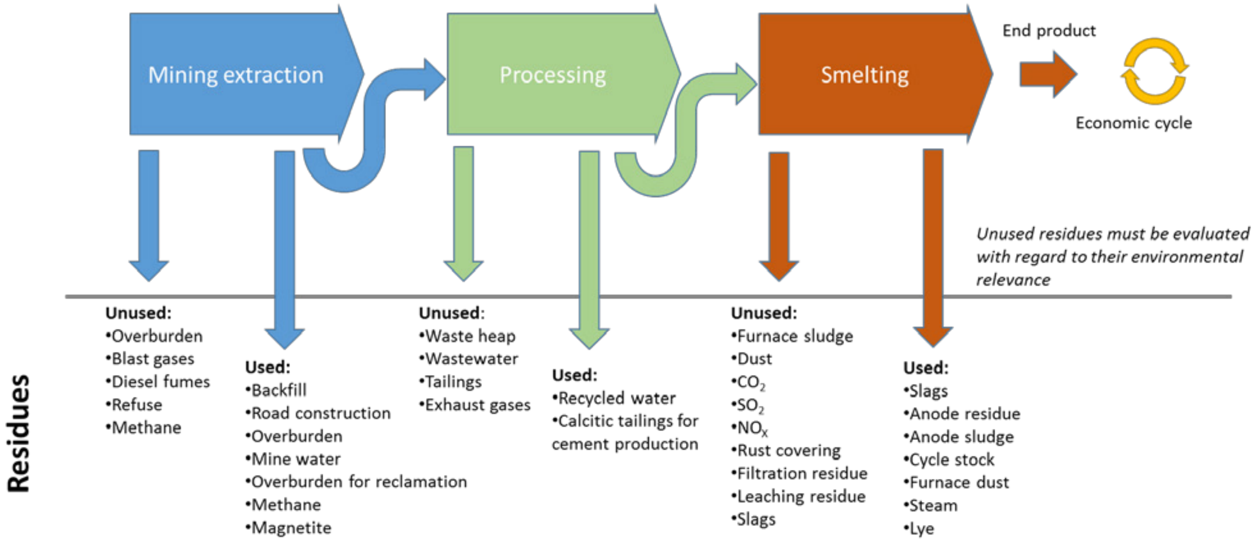
This type of illustration makes it possible to show which raw materials have a high, medium or low environmental hazard potential, irrespective of their assessment with regard to the supply risk. In conjunction with vulnerability, it also shows whether raw materials that have so far not been classified as critical require a higher level of attention in consideration of the environmental dimension. It also shows which raw materials already classified as critical also have an environmental hazard potential. In the example, raw material A is the least critical followed by raw material B. Raw material E is the most critical. Raw materials C and D exhibit similar environmental criticality, even though raw material C shows higher environmental hazard potential and raw material D has a higher vulnerability.

6 Mining residues

As a particular focus of the project, a characterisation was made of "unused extractions". Significant in the discussion on resource conservation is here the classification of key terminology in the mining context, e.g. the distinction between used and unused extractions that are applied differently. Figure 4 illustrates the conceptual understanding in mining for used and unused mass flows. It differs from the conceptual understanding of economic material flow accounting for used and unused extractions.

Within the scope of the project, our own report on this subject[5] was compiled and discussed in a technical workshop.

Figure 4: Mass flows of the raw material extraction according to BGR 1998



Source: Authors' illustration

Causes for the origin of mining residues from mineral extraction and processing are e.g. the removal of the barren overburden, the excavation of mine workings in the country rock, e.g. the separation of ore with content below the cut-off grade, the separation of non-valuable material during processing, incomplete recovery and losses of valuable mineral during transport as well as in the smelting process.

Decisive for the amount of residues in relation to exploitable mineral quantity are, besides the geometry of the deposit (massive or vein deposit) and the selected development and mining method (unconsolidated sediment mining, hard-rock open pit mining, underground mining etc.), in particular the raw material-specific grades of the deposit. These grades differ in part very significantly: minable iron ore normally has a haematite content that is clearly above 50 %. In sharp contrast to this, diamond deposits have a typical diamond content of about 1 carat per metric tonne, i.e. 0.2 grams per metric tonne or a content of 0.00002 %. In the case of iron, the valuable mineral/residue ratio is therefore about 1:1, whereas for diamond it is 1:5,000,000. For the most important metallic and non-metallic mineral raw materials, the average grades have been determined from existing data sources.

Independent of their material composition, the mining residues have alone through the moving and depositing of the material the following impacts on the environment:

- Land-take through the extraction operation and waste heaps/tailings ponds for residues,
- Vegetation and soil destruction through removal and covering,
- Loss of habitat, landscape change,
- Silting of surface water through erosion of the residues, quantitative intrusion in the local water balance through sealing, drainage, etc.

Besides the amount itself, there are however still numerous further effects on the environmental relevance of the mining residues such as in particular the physical and chemical properties and the content of toxic ingredients, from which further environmental risks originate:

5 For reference source see Footnote 2

- Acidification, sour water, acid mine drainage
- Soil and water pollution through reagents from extracting and processing, toxic substances from mineral mixtures, dissolved substances and those that pass into solution due to auto oxidative processes.
- Dust pollution through discharge (mostly wind erosion), in particular in regard to asbestos, coal dust, quartz and siliceous minerals.
- Contamination of rivers through mineral suspensions,
- Radioactivity, radiation exposure,
- Risks through unstable disposal conditions on waste heaps, tailings ponds.

In order to facilitate an estimation of the environmental relevance of the mining residues per raw material, an evaluation system was compiled and applied to the residues of selected raw materials (Table 8).

Table 8: Comparison of the environmental relevance of mining residues according to various criteria for gold, copper, potash, coal, iron and aluminium/bauxite

	Gold		Copper		Potash		Coal		Iron		Alumi-nium		Dia-mond	
	M	P	M	P	M	P	M	P	M	P	M	P	M	p
Physical														
Particle size / air exposure	red	red	green	red	green	red	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow
Aggregate (solid/liquid)	green	red	green	red	green	red	yellow	yellow	green	yellow	yellow	red	yellow	yellow
Chemical														
Composition	yellow	yellow	green	red	yellow	red	yellow	yellow	green	green	yellow	yellow	green	green
Contaminants/reagents	green	red	green	red	green	green	green	green	green	yellow	green	red	green	green
Mass balance														
Mining residues per t raw material	green	red	green	yellow	green	green	green	green	green	green	green	green	red	red
Environmental relevance														
Radioactive	green	green	green	green	green	green	green	green	green	green	green	green	green	green
Auto oxidative	yellow	red	green	red	green	green	green	green	green	green	green	green	green	green
Toxic	green	yellow	green	red	yellow	red	green	yellow	green	green	green	green	green	green
Storage type														
Waste heap	green	red	green	red	green	red	green	yellow	green	green	green	yellow	red	red
Tailings pond	green	red	green	red	green	green	green	yellow	green	yellow	green	red	green	green
Others	green	red	green	green	green	red	green	green	green	green	green	green	green	green
Use options														
Building materials	green	green	green	green	green	green	green	green	green	green	green	green	green	green
Backfill	green	green	green	green	green	green	green	green	green	green	green	green	green	green
Others	green	green	green	green	green	yellow	green	green	green	green	green	green	green	green

M= Mining, P= Processing
green = low EHP; yellow = medium EHP; red = high EHP (where EHP = environmental hazard potential)

Even when taking into account the limits of the evaluation system, the results make clear that:

- The environmental relevance of the residues from processing is as a general rule significantly larger than that of the residues from the mining extraction. The residues from processing are included in the economic material flow accounting of used extractions and are mapped also into the "raw material input" (RMI) economic material flow indicator. This is based on the "total raw material productivity" indicator of the new edition of the National Sustainability Strategy and of the German Resource Efficiency Programme (ProgRess II).
- Particular environmental risks and environmental interventions come from those residues that are deposited in fine fraction in tailings ponds, on waste heaps or submarine. This is due on the one hand to the complicated stabilisation of the residues and on the other hand to the high surface activity of the fine and finest particle sizes.

7 Recommendations for action

The methods developed in ÖkoRess I for the initial assessment of the environmental hazard potentials of individual mining projects, of mining residues as well as of abiotic raw materials are based on numerous available scientific analyses and results, but represent innovations nevertheless in terms of their methodological approach and display in an impressive manner the range of possible environmental impacts originating from mining. The consequences of the environmental impacts are illustrated likewise by many of the 40 case studies that in particular have led to a realisation that the effects caused by mining are very heterogeneous, both in terms of type and magnitude, and depend on the raw materials mined in each case, as well as on site-based factors and the environmental measures implemented. It is thereby worthy of note that indeed in many places environmental measures are undertaken, but that these mostly do not suffice in order for all environmental impacts and accident hazards to be reduced to a possible minimum. At the same time, mining continues to be encountered in many world regions that observes no environmental protective measures whatsoever. The following recommendations for action can be derived based on these findings as well as on further results presented in this document:

- Because Germany is dependent to a very great extent on the import of abiotic raw materials, many value chains are associated with negative environmental impacts from mining in other world regions. Furthermore, environmental impacts are often unequally distributed along the global value chains: While a majority of economic value addition occurs in industrialised countries with comparatively controlled environmental impacts, mineral extraction and processing are associated in many places with extreme local environmental impacts that would not be accepted in this form in many industrialised countries. This connection results in an ethical co-responsibility for industry and policy in Germany. In particular, the raw materials policy is in demand for taking up as core objective not only the interest of supply security but also that of environmental aspects for mining and processing and – together with industry – to carry it over into appropriate measures.

- For the planning and design of effective measures, a reduction of complexity is indispensable as a first step. It is recommended that measures focus first on those raw materials that on the one hand exhibit a particularly high environmental hazard potential from an environmental point of view, and on the other hand have a high economic significance for Germany and the EU, i.e. environmentally critical raw materials. The method for raw material-related evaluation developed in ÖkoRess I enables such a prioritisation and is applied to over 50 abiotic raw materials in the ongoing follow-up project (ÖkoRess II). Such prioritisation can also be used by companies for their efforts to achieve sustainable supply chain management[6].

- For the debate on science and industrial policy on critical raw materials, it is recommended to examine to what extent the method developed here can be included in the existing criticality assessment. Generally, efforts should be made for raw material-related evaluation systems to give a comprehensive overview of raw material-related risks and impacts. Environmental problems and impacts ought to be treated transparently in an equal manner and mapped as a separate evaluation dimension. Such an integrated presentation is also effective because environmental hazard potentials are likely to have a significant impact on future price and scarcity developments as a result of an expected increase in the internalisation of external costs in the mining sector, thus providing an important additional information basis for a sustainable raw material policy.
- Site-related decisions – whether for the (co-)financing of mining projects, the acquisition of ores and concentrates from remote mining projects or the independent assessments of as yet unrecorded impacts and risks – require a sound scientific basis, which however can only be established in many cases with substantial financial and logistic efforts. For many stakeholders in industry, finance and civil society, drafting such comprehensive assessments only then comes into question when projects take form or initial reports on environmental problems become known. This gap can be filled in by both methods presented here for the estimation of environmental hazard potentials of individual mining projects and of mining residues. Indeed, these methods cannot and should not replace any comprehensive environmental impact assessment, but can facilitate robust initial assessments for companies, financial institutions and civil society groups and can be used as an initial "hazard radar" for environmental issues.
- A further field of application of such a "hazard radar" rests with decision-makers and geological services in developing countries. While as a general rule the relevant committees and authorities have very limited personnel and financial resources, the task of inspecting contract awards and mining operations in terms of their environmental impacts and providing, if applicable, relevant restrictions and conditions /obligations is nevertheless incumbent upon them. Indeed even here the site-related evaluation method presented cannot replace any well-developed environmental impact assessments but it provides nevertheless a good approach in order to give robust initial assessments and to plan further investigations with comparatively low expense.

The methods presented facilitate thereby, as explained, an initial estimation at reasonable expense in line with an "overview radar". Thereby, the raw materials can be identified for which a closer examination of the environmental hazard potentials is particularly necessary. They provide guidance on which areas special attention is needed. Even with regard to individual sites and mining residues, the indications obtained are in this sense in support of an urgently required, detailed on-site environmental impact study. It is absolutely important to take into account the limits of significance due to collection options being to some extent only generalised.

[6] See also: BMUB (2017): Schritt für Schritt zum nachhaltigen Lieferkettenmanagement – Praxisleitfaden für Unternehmen (Step by step to sustainable supply chain management – Practical guide for companies). Internet: www.bmub.bund.de/N54211/