Protocol on Environmental Assessment of CRM extraction in protected areas

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Executive summary

This report reviews the mid- to long-term environmental and societal impact of extractive activities in environmentally protected areas, i.e., looking at any real-cases performance gaps with a view to compare what was expected from technologies, processes and strategies at the design/permitting stage and what communities and ecosystems will experience at the implementation stage. Current extraction methods have been subject to a stakeholder value-driven assessment from an environmental and societal perspective. Risks and impacts are considered in the long-term, from the construction of extractive facilities/infrastructure to closure, rehabilitations and possible constraints on the rehabilitation and after-use of such sites. In addition, in a systemic and comprehensive environmental assessment, other impacts and risks, such as health & safety risks to workers, communities, and natural ecosystems have been taken into consideration. This evaluation builds inter alia on international experience, the principles of environmental impact assessments, recent guidance by the European Commission on the management of extractive waste (c.f. MWEI-BREF) and on risk assessment in the extractive industries.

The dimensions to be taken into account in the assessment of implications of CRMs extraction in environmentally protected areas have been defined, considering nature conservation factors (e.g., natural values protected), mining processes/technologies used and the given geological settings (e.g., type and characteristics of CRMs' deposits). This allows to appropriately cross-reference natural values protected/to protect, the drivers behind societal CRMs needs by framing it in a DPSIR (Drivers-Pressures-States-Impacts-Response) model and extraction methods and technologies, at the earliest stage of permitting procedures.

The analysis of technical feasibility reveals that deep mining operations employing advanced automation, underground processing, and precise drilling techniques can significantly reduce surface impacts. Modern water management systems and paste backfilling methods demonstrate particular promise in minimising hydrological disruption. However, the effectiveness of these techniques is highly site-specific and depends on geological conditions. Emerging technologies continue to expand the possibilities for low-impact mining, though their application must be carefully evaluated within each specific context.

Impact pathways vary significantly between different types of protected areas and mining configurations. The assessment of potential impacts must consider groundwater systems, ecosystem connectivity, and cumulative effects. Long-term environmental management requirements need to be integrated into project planning from the outset.

On this basis, a decision-making protocol is proposed that allows to adequately evaluate and balance the potentially conflicting societal expectations and needs between environmental protection and providing for a sustained socio-economic development. The protocol uses a structured three-tier assessment process, that begins with a policy-level evaluation of critical raw material needs, proceeds through technical and economic feasibility assessment, and concludes with site-specific environmental impact evaluation. The DPSIR (Drivers-Pressures-State-Impact-Response) framework used provides a systematic approach to balancing competing societal needs, while performance evaluation systems ensure ongoing project viability.

The extraction beneath protected areas may be justified and feasible in specific circumstances where there is a demonstrable critical raw material need, geological conditions allow for minimal surface impact, appropriate technologies and management systems can be implemented, environmental values can be adequately protected, and stakeholder concerns can be effectively addressed. But implementation of extraction projects beneath protected areas requires rigorous initial assessment, comprehensive monitoring systems, adaptive management capabilities, clear performance thresholds, strong stakeholder engagement, and long-term management commitment.

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1 Introduction

1.1 Background and objectives

Work-package 4 of the project CIRAN is concerned with the assessment of 'best available' techniques and processes covering the whole extractive life-cycle (exploration to rehabilitation and preparation for a sustainable and beneficial after-use of brownfields), and the explanation of the design performance gap, contrasting expected and 'in use' environmental and social performance of extractive projects. Elements of the appraisal include technologies and industrial processes used, project conception and construction approaches, assessment of permit applications by competent authorities, acceptance by the local communities and governance models, from inception to project closure. This life-cycle oriented, that begins at the exploration phase, approach will also be used to check how extraction activities adapt to regulatory constraints and social expectations across time, providing a comprehensive overview of low-impact and low-visibility extraction options that meet local stakeholder expectations. The evaluation of mine development effectiveness and what might be considered good/best available techniques and processes will be based on a mechanistic understanding of the ecosystem in or near which a mining operation is located, following the source-pathway-receptor risk model. Opening up new exploration and extraction scenarios will also provide incentives for the industry to (further) develop suitable technologies, business and governance models.

There are scenarios in which a mine a considerable distance away can have a significant impact on a protected area, while a deep mine underneath may not have any impact at all. The aim is to identify cutting edge and emerging mining technologies and strategies, providing a state-of-the-art picture of low-impact and low-visibility extraction options. The results of the investigation will flag options and limitations for extraction methods that may be considered for use in environmentally protected areas.

Task 4.1 of CIRAN has investigated current and advanced extraction methods (technologies, processes and strategies used across the mine life-cycle, from the exploration stage to closure and remediation, and provided an overview over relevant technologies (Carriedo et al., 2024).

Reference documents at EU level to be considered include the best-practice guide on extractive waste management (MWEI-BREF, 2018) and the forthcoming guidance on risk management in the extractive industry (Eco-Efficiency, 2024).

Insights from WP4 will be used in WP5, WP6, and WP7, and the CIRAN Experts Group's direct engagement has brought realistic views on the process of decision-making towards permitting.

1.2 Target audiences

This report aims to inform planners, regulators and other decision-makers on the technical and strategic planning options for a low-visibility and low-impact mine. It will also help to inform the discussions with public stakeholders with a view to improving their understanding of mining operations. However, no particular effort was made to avoid technical language.

Certain mining technologies or strategies (e.g. underground vs. open-cast mining) that may be favoured for technical or economic reasons by the operator may not find acceptance by regulators or the general public. The 'protocol' developed will help to resolve such issues and find alternative solutions with which all stakeholders can live.

2 Understanding natural values and conservation factors

2.1 Definition and classification of environmentally protected areas

In the following the types of protected areas will be discussed from the perspective of the ecosystems, environmental compartments and ecosystem functions, rather than from the administrative and regulatory perspective (cf. WP3). This allows a better understanding of how these aspects and functions can be protected from a functional point of view and which mining strategies and technologies would be conducive to it. An analytical-reductionist approach is helpful, but could also be misleading, as at many natural sites all the aspects listed below are relevant, but this approach allows for a better understanding, which mining strategy and technology would be the most protective.

A protected area is a designated geographical space managed to conserve its natural, cultural, and historical resources. These areas are managed to ensure the protection and preservation of flora and fauna, ecosystems, and cultural sites from human activities that may harm them. Protected areas are essential for biodiversity conservation, environmental sustainability, and providing opportunities for outdoor recreation and education.

Protected areas are classified into various categories by IUCN (International Union for Conservation of Nature): nature reserves; wilderness areas; national parks; national monuments; habitat/species management; protected landscape/seascape; protected areas with sustainable use. Other protected areas include Ramsar sites (wetlands), MAB areas (Man and Biosphere reserves), UNESCO Geoparks (Global Geoparks Network).

2.2 Identifying and assessing natural values and conservation factors

2.2.1 Overview

An appropriate approach to the analysis of biodiversity distribution must necessarily involve knowledge of the portions of territory that are functional for the conservation of wild species, known as the 'ecological network'. In recent years, the notion of ecological network has been used in many scientific fields as a theoretical and practical reference for the environmental functionality of a territory. This widespread use is due to its characteristics as a highly versatile conceptual tool, applicable in a wide range of contexts, effectively schematizing various natural and anthropogenic phenomena in which elements of different functionality intertwine like the meshes of a net.

There are four main areas in which the concept of an ecological network is applied (e.g. Reggiani et al., 2000):

- in territorial planning, where the network is the tool that allows the representation of the dynamism and interdependence of natural and anthropogenic components;
- in 'sustainable' socio-economic development programs, where the network has been used to flexibly represent resources, flow of information, skills, and services compatible with the conservation of the territory's natural resources;
- in the design of an integrated system of protected areas and in the evaluation of their effectiveness;
- in the scientific disciplines of ecology and conservation biology, where the concept of a network effectively synthesises the dynamics underlying the distribution of life forms in the territory and the interrelations among them.

In all these areas, the identification of an ecological network mostly involves three phases:

1. identification of the elements of the network;
2. identification of areas with ecological connection functions (e.g., protected areas);
3. identification of the different functionalities of the elements within the system.

As previously stated, ecological networks are a concept of particular importance for sustainable land use planning and nature conservation. This concept is shaped by the obvious observation that all species are distributed non-uniformly over the territories, and that this discontinuity is primarily due to the action of intrinsic natural factors upon which anthropogenic factors act and intervene. It is evident how the concept of an ecological network manifests in practice in a completely different way depending on the taxonomic group under consideration. The overall ecological network results in a dense fragmentation of the territory into homogeneous areas, representing the real global ecological network that exists on the territory (Reggiani et al., 2001).

2.2.2 Biodiversity

Evaluating the importance of biodiversity is essential to understand the significance of potential environmental impacts and prioritise mitigation measures. Assessing importance is a complex challenge for mining companies. Over the past few decades, there have been many publications regarding the assessment of nature conservation, providing guidance. Although there is no universal standard, some common criteria include the following:

Species/habitat richness: Generally, the greater the diversity of habitats or species is in an area, the more valuable and most likely resilient the area is. Thus, habitat diversity within an ecosystem can be highly valuable and determine the likely response to disturbances. A mosaic of habitats adds particular value, since some species depend on more than one habitat types and in consequence can live in the transition zone between habitats.

Species endemism: By definition 'endemic' species only occur at one geographically defined location in the world. Endemic species are typically found in areas where populations of a given original species have been isolated long enough to develop distinctive characteristics, which eventually prevent interbreeding with populations of the original or other species.

Keystone species: A keystone species is one that exerts significant influence on an ecosystem relative to its abundance or total biomass. For example, a key predator can prevent its prey from overpopulating an ecosystem. Other keystone species act as 'ecosystem engineers', for instance, transferring nutrients between ecosystems or their components. In consequence, the fact that a given ecosystem critically depends on such keystone species undermines its resilience as a whole, as any negative impact on this species threatens the ecosystem as whole.

Rarity: The concept of rarity can apply to ecosystems and habitats as a whole, as well as individual species. Rarity is considered a measure of susceptibility to extinction, and the concept is expressed in various terms such as vulnerable, rare, threatened, or endangered. However, one has also to make a distinction, whether a species is (or has become) rare in a given habitat or ecosystem or is rare on a global level.

Habitat size: The size of a natural protected area is generally considered important with respect to resilience. It must be large enough to be able to buffer ecosystems and habitats from activities at their margins, species loss, and colonisation by unwanted/invasive species. Habitat connectivity is also considered important and refers to the extent of connections between areas of natural habitat – high levels of connectivity between different habitats or portions of the same habitat ensure inter alia a sufficiently large gene pool to keep species viable and prevent inbreeding. For some large predators, it is crucial that the protected area is large enough to encompass the home range of several individuals and allow them to breed and be sustained.

Population size: Species with large population sizes and geographic ranges are less likely to go extinct than species with small populations and limited geographic ranges (IUCN, 2024). For some large predators, it is important to know, whether an area is large enough to encompass the home range of several individuals and allow them to breed and be sustained.

Fragility: This refers to the sensitivity of a particular ecosystem or habitat to human-induced or natural environmental changes and its resilience to such changes. In recent years climate change may add to the fragility of certain ecosystems or habitats due *inter alia* to changing rainfall patterns leading to droughts or flooding, changed growing seasons, improved conditions for pests, etc.

The importance of biodiversity as one element of the ecosystem services provided to mankind is discussed in context and more detail in Section 2.2.5.

On the other hand, mining activities are known to have eventually increased the biodiversity of certain areas. For instance, excavations have given rise to wetlands or surface water bodies, a process that can be encouraged during remediation activities. Conservationists my view this with mixed feelings, as this objectively increases the biodiversity of an area, but at the same time may introduce or attract species that were not present there before. In turn, given that such habitats do not exist in isolation, the surrounding ecosystems will be influenced by them, altering their biodiversity. Resulting discourses may be more at the normative-ethical level than at a scientific-functional one.

2.2.3 Geological and geomorphological features

While exploiting elements of the local geology at the surface or more likely at depth, mining can significantly alter the local landscape and other features, such as the local or regional hydrology or soils. As mining depends on the geological occurrence of minerals of interest, their form of occurrence has a significant influence on the mining techniques or mine layout and, hence on how the mine alters the geological and geomorphological surroundings.

The geological and geomorphological features can be valued per se, for instance due to scientific value or due to their aesthetic or emotional value as landscape. Recognising these values, in more recent years so called 'geoparks' have begun to be set up that protect sites of particular geological or palaeontological interest in addition to certain landscapes that have been already protected under various other instruments.

There are number of effects resulting from mining activities that can detriment these values and the associated ecosystem services (see preceding section), including:

Disturbance of land: Mining activities, particularly also open-cast mining, can result in the physical disruption of the land, leading to changes in topography/geomorphology, loss of topsoil, deforestation, and ensuing modification or destruction of natural habitats. This constitutes also a permanent change of land use.

Soil erosion: Mining can enhance soil erosion by removing vegetation and exposing bare soil to increased runoff. This in turn can lead to increased turbidity and sedimentation in downstream water bodies, affecting water quality and aquatic ecosystems. At the same time the increased surface runoff leads to a reduce infiltration and, hence, less groundwater recharge.

Groundwater depletion: Mining operations in most cases require a lowering of the local or even regional water table in order to provide access to the underground mineral resources of interest. This will significantly alter the respective hydrological balances and can lead to a depletion of groundwater resources and changes to the surface flow pattern in the surrounding area. In turn this can be detrimental to biodiversity features, such as wetlands, or prevent access to groundwater resources for the production of e.g. drinking water.

Ground- and surface water quality: A mine and its associated extractive waste facilities can have detrimental effects on the quality of ground- and surface waters in the area by generating acid, alkaline, or saline effluents that may in addition introduce toxic or radioactive contaminants. Thus, the value of the water resources for local ecosystems and communities can be negatively impacted.

Subsidence: Certain underground mining techniques can cause, in the longer term, subsidence, which is a sinking/depression of the land surface when underground voids collapse. Subsidence can damage infrastructure or houses and change, depending on its scale, the local or regional surface drainage patterns.

Changes to the geological risk status: Mining activities and the associated processes discussed above can impact local or regional geological or hydrological equilibria. Their re-equilibration can be sudden and spontaneous, leading to rock-falls, landslides, seismic activity, activation of fault zones, flooding and others.

Alteration of topography and geomorphology: The excavation of open pits and the construction of extractive waste facilities, such as spoil heaps and tailings ponds, can significantly alter the local geomorphology and thus drainage and erosional patterns.

Visual and aesthetic value: Mining operations can alter the visual appearance and the aesthetics of the landscape, often resulting – before remediation - in unsightly scarred land, new features such as spoil heaps or tailings ponds and industrial structures. It should be noted, however, that some of such features can also become elements of the cultural heritage (e.g. the cone-shaped heaps that evolved over decades or centuries in some regions, the iconic mine buildings of Cornwall, etc.) or add to the biodiversity (e.g. lakes and wetlands in former open-cast mines or quarries) – see also above the discussion on introduced biodiversity.

2.2.4 Cultural and historical values and heritage

While people are certainly attached to the features and elements of their local built and natural environment, in some instances these have value beyond the region or even at global level. Historical buildings and structures are obvious examples, but the overall appearance of man-made landscapes (e.g. the Scottish Highlands) or groups of 'holy' trees can have important significance to local populations and beyond. Many of such sites today are protected under various instruments, the most important of them are probably designated World Heritage Sites (https://whc.unesco.org/). It should be noted that the discourses around the protection of cultural heritage are largely driven the various normative and value systems of the stakeholders concerned.

Mining activities can impact such sites and areas in a variety of ways, including:

Destruction: As mining operations involve a temporary or permanent change in land use, it can result in the destruction or damage of cultural heritage sites, such as traditional villages, burial grounds, sacred sites, and archaeological sites. This in turn can lead to the loss of important cultural artifacts, knowledge, and traditions that are critical to preserving the history and identity of a community or a region. The choice of mining techniques and strategies can significantly determine the kind and seriousness of impact.

Visual impact: The cultural and historical value of a landscape can be significantly compromised by mining installations (and indeed other industrial installations or buildings) or the new landscape features mining creates, even if these are outside the actual protected area.

Displacement of communities: Mining activities can lead to the displacement of indigenous communities and other marginalised groups from their ancestral lands, disrupting their cultural traditions, connections to the land, and social structures. This can result in the loss of traditional knowledge, languages, and customs that have been passed down through generations. While this concerns mainly mining in emerging economies and developing countries, it did occur in the past in Germany, Poland and Czechia in areas of large-scale open-cast lignite mining, where whole villages had to make room to mining.

Impacts on traditional ways of living: In particular rural communities may make extensive use of natural resources, such as small-scale agriculture, horticulture, fishing, local drinking water supply etc. which may be negatively impacted by contaminated effluents or emissions from mining activities and their extractive waste facilities. This can have detrimental effects on the health and well-being of such communities who rely on these resources for their cultural practices and livelihoods.

Changes in social dynamics: The influx of mining workers and infrastructure can bring about rapid social changes in a community, leading to increased tensions, conflicts, and social disruption. Local people may also use the opportunity to work as miners, with eventual abandoning of traditional economic sectors. This can impact the cohesion and unity of a community, as well as erode traditional systems of governance, decision-making, and social norms. The kind and severity of such impacts also depend on the duration of the mining activities and the ratio between existing populations and new arrivals. Several regions across Europe historically and more recent times experienced significant influxes of foreign workers due to a booming mining sector with eventual complete assimilation and development of a joint culture. A point in case are the coal-mining districts in NW Germany that saw a large influx of Polish families in the last quarter of the 19^{th} century, who quickly became integrated.

Loss of cultural identity: The destruction of cultural sites, displacement of communities, and contamination of cultural resources can all contribute to the loss of cultural identity and heritage. This can lead to a sense of disconnection, alienation, and loss of cultural pride among affected communities, as their cultural values and traditions are undermined and devalued by the impacts of mining. Again, this is less likely to happen under the conditions in which mining in Europe will occur.

2.2.5 Ecosystem services and functions

The crucial importance of ecosystem services for our lives is now widely appreciated. While assessment techniques are still under development (see below), concerted efforts need to be made to address this aspect. The identification and assessment of impacts involve recognising effects on nature and essential ecosystem services.

Ecosystem functions: are the individual functions that are necessary to make ecosystems or indeed the biosphere as a whole work. They include essential processes, such as primary production (photosynthesis), nutrient cycling, soil formation and conservation, regulation of climate and hydrological flows, water purification, and erosion control. These functions support biodiversity and provide the basis for the ecosystem services that benefit humanity. De Groot et al. (2000) note that although a wide range of ecosystem functions and their associated goods and services have been referred to in literature, their experience suggests that it is convenient to group ecosystem functions into four primary categories:

1 - Regulation functions: relate to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through bio-geochemical cycles and other biosphere processes. In addition to maintaining ecosystem (and biosphere) health, these regulation functions provide many services that have direct and indirect benefits to humans (such as clean air, water and soil, and biological control services).

2 - Habitat functions: natural ecosystems provide refuge and reproduction habitat to wild plants and animals and thereby contribute to the (*in situ*) conservation of biological and genetic diversity and evolutionary processes.

3 - Production functions: Photosynthesis and nutrient uptake by autotrophs converts energy, carbon dioxide, water and nutrients into a wide variety of carbohydrate structures which are then used by secondary producers to create an even larger variety of living biomass. This broad diversity in carbohydrate structures provides many ecosystem goods for human consumption, ranging from food and raw materials to energy resources and genetic material.

4 - Information functions: Because most of human evolution took place within the context of undomesticated habitat, natural ecosystems provide an essential 'reference function' and contribute to the maintenance of human health by providing opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetic experience.

Environmentally protected areas aim to ensure one or more of the above ecosystem functions. On the other hand, we humans interact with the environment in a wide variety of ways, profiting from the services these ecosystem functions provide us with.

Ecosystem services: are those functions that enable the human species to survive and thrive (De Groot et al., 2002). They include 'services' that enable life in general, but also interactions with man-made impacts and stresses, such as waste or water pollution. In this sense the services are defined from a human perspective, but keeping the functioning of ecosystems as a whole in mind also. Thus, the functioning of the hydrological systems provides us with the essential supply of drinking water as well as water for agriculture and industrial purposes. Furthermore, functioning hydrological systems are the basis of all ecosystems that support life.

Different environmental compartments provide different ecosystem services. Soil and aqueous ecosystem receive solid and liquid wastes and are able to decompose organic pollutants and contaminants. Soils recycle nutrients thanks to soil organisms and aid in regulating local climate by supporting the plant cover that recycles greenhouse gases. Soils and plant cover are also important elements of the hydrologic cycle by ensuring groundwater recharge and flood protection due to its buffering capacity, retaining precipitation. Plants through their root system counteract erosion and thus maintain the soil profile that is needed for agriculture. The storage capacity for water of soils and the shallow geological strata ensure that groundwater remains available even in periods of droughts.

Another important function relates to the ability of ecosystems to ameliorate 'natural' hazards and disruptive natural events. Forests in Alpine areas protect settlements from the effects of avalanches. Coastal (coral) reefs protect islands and low-lying coastal areas of the tropics from the action of waves. Thus, providing safety of human life and human built infrastructure is an important ecosystem service.

While the atmosphere provides the important service of receptor for gaseous waste materials from human activity, such as greenhouse gases, the plant cover around the world is a critical sink for carbon due to its capturing it in form of CO_2.

Soils and plants are not only the basis for agriculture, but also for hunting, beekeeping and timber production, while fresh and seawater furnish humanity with fish and seafood.

While not absolutely necessary for survival, many ecosystems add to our well-being by providing aesthetic pleasure and space for recreation and tourism (various articles in Tampieri, 2010).

Potential threats to these services that support our livelihood by mining activities are discussed in more detail below. The importance of ecosystem services as a systemic approach is a relatively new topic for EIA. Environmental Impact Assessment must develop and utilise appropriate ecosystem service assessment methodologies that reflect the importance of local ecosystem services (ICMM, 2006).

Water quality and availability: Mining operations can contaminate, as discussed above, water resources with toxic chemicals and heavy metals, which can make the water unfit for human consumption and other uses. Treating such waters adequately will entail considerable costs and result in an added carbon-footprint. Mining effluents can also indirectly affect other ecosystem services due to the lack of availability of clean water for agriculture, fishery due to the harm to aquatic ecosystems and general loss of biodiversity.

Soil quality and fertility: As noted above, mining activities often involve the clearing of vegetation and the disturbance of soil, leading to soil erosion, compaction, and contamination. Uncovered spoil heaps and dried out tailing ponds can also give rise to wind erosion and the dispersal of contaminated dust. This can result in reduced soil fertility, decreased agricultural productivity, and loss of habitats for plant and animal species.

Biodiversity loss: Biodiversity is a key feature that ensures the resilience of ecosystems and, hence, their services. Mining can result in the local destruction and fragmentation of habitats, which then may not be able anymore to support certain species, manifesting itself as a loss of biodiversity. The disruption and fragmentation of ecosystems can impact the interactions between species, disrupt food chains, and thus alter ecosystem dynamics, resulting in long-term ecological imbalances.

A comprehensive risk catalogue that also includes biodiversity risks can be found in Appendix 1.

Air pollution: Clean air is a vital ecosystem service for most species including us humans. Mining and processing operations can release dust, particulate matter, and other pollutants (including greenhouse gases) into the air. This air pollution can lead to respiratory health problems in nearby communities. Dust dispersal and sedimentation on plants can significantly impair their ability to photosynthesise and thus impair their ecosystem service of carbon sequestration and regional humidity regulation. The emissions of greenhouse gases and other pollutants will also contribute to climate change and impact air quality on a regional and global scale.

Carbon sequestration: Vegetation and in particular forests provide the important ecosystem service of carbon sequestration (in addition to rainwater retention and local climate regulation). Deforestation and land clearing for mining activities can reduce the capacity of local/regional ecosystems for provide this service and mitigate climate change. Removal of vegetation in itself is likely to release carbon stored in the plant matter.

Water retention and buffering in the hydrological cycle: Top-soils and vegetation provide the vital ecosystem function of water retention, ensuring groundwater recharge, and thus to even out the effects of precipitation events. Top-soil removal and de-vegetation/deforestation, therefore, deprives an area of this important function. In addition, it can lead to increased erosion, turbidity, and eventually sedimentation rivers, streams, and other surface water bodies. This in turn affects other ecosystem functions linked to water quality, aquatic ecosystems, and riparian habitats. The resulting destabilisation of ecosystems and loss of aquatic biodiversity will impair the ecosystem service of natural water purification.

It should be noted that the extent and severity of such effects and the resulting loss of ecosystem services strongly depends on the spatial extent and location of the mining operation and its associated extractive waste facilities, which will need to be optimised in this respect to minimise such impacts. Locations for surface installations of deep mines can be chosen to minimise impacts. Carefully planned, concurrent and proactive remediation measures, such as revegetation, can mitigate many of the above detriments to ecosystem services.

2.2.6 Environmental and social impact assessment

Environmental and Social Impact Assessment (ESIA) is an important tool for ensuring that biodiversity is integrated into project planning and decision-making. The ESIA process provides a structured approach which encompass the environmental, economic and social consequences related to options and alternatives when developing a mining project (ICMM, 2006), although in Europe currently only Environmental Impact Assessments (EIA) are codified (see CEU 2014 and the corresponding national legislation).

In order to take into account of the various aspects of nature conservation, the ESIA needs to assess the relevant levels of biodiversity; assess the interconnections between the levels of biodiversity by considering the structural and functional relationships and how they will be affected by the proposed project; collect detailed data of key biodiversity indicators; assess the full range of impacts, including primary, secondary, cumulative and induced impacts; assess the importance of community and indigenous knowledge of local biodiversity aspects and stakeholder participation; clarify the criteria used to assess impacts; and consider impacts and mitigation measures for biodiversity.

It is important to recognise that the application of ESIA benefits greatly from being conducted within an overall strategic planning framework in which the development and conservation of land potential has been considered in an integrated manner at a regional level, also taking into account territorial planning. Region here does not mean an administrative unit (as in certain countries, such as Italy or France), but an area in which functional relationships exists, such as in a catchment area.

Although legislative requirements and practices vary around the world, the fundamental components of an ESIA of relevance to nature conservation include many phases that will be discussed in the following paragraphs (see also the EIA Directive, CEU, 2014).

Conduct environmental impact assessments (EIAs): Prior to initiating mining activities, conduct comprehensive EIAs to evaluate the potential environmental impacts of the project. This involves assessing the existing environmental conditions, identifying sensitive areas and ecosystems, and predicting the potential impacts of mining activities on the environment.

Identify environmentally sensitive areas: Identify and map environmentally sensitive areas, such as protected areas, critical habitats, water bodies, biodiversity hotspots, and culturally significant sites. These areas are considered high priority for protection due to their ecological value and vulnerability to disturbance.

Thus, an ESIA begins with the screening or scoping to identify environmental and social aspects to evaluate and determine the level of assessment needed. Initial steps include:

- Gathering available biodiversity information through available (e.g. on-line) maps and publications,
- Determining, if the area is designated for biodiversity protection and if so at what level,

- Identifying high-priority conservation areas, even if not currently protected,
- Recognising, if the area hosts particular species that might be threatened,
- Reviewing current legal provisions related to biodiversity,
- Soliciting stakeholder opinions on the site's traditional or cultural value,
- Delineating the area to investigated, based on likely functional relationships within ecosystems.

Baseline studies are essential for impact prediction, and later monitoring as well as assessing mitigation success.

For **new projects**, collecting detailed baseline data is important, where initial mapping indicates areas with significant biodiversity aspects needing further study, the surrounding land has a particular biodiversity value and faces already threats, and when important biodiversity areas are adjacent to a proposed operations with complex use patterns.

For **existing projects**, additional fieldwork may be needed, where long-term operations lacked initial biodiversity assessments, post-closure land use includes biodiversity conservation or enhancement provisions, and where unintended negative impacts on biodiversity has occurred.

Evaluating biodiversity importance is crucial for understanding the significance of potential environmental impacts and determining mitigation priorities. For existing protected areas and species, the importance is at least partially identified by their classification as e.g., World Heritage Sites or Ramsar Sites (which hold international significance), or IUCN (Dudley, 2008), that are nationally important. It should be noted that IUCN Category Ia sites are strict nature reserve and thus are strictly protected for biodiversity and also possibly geological/ geomorphological features, where human visitation, use and impacts are controlled and limited to ensure protection of the conservation values.

However, evaluating biodiversity importance in non-protected, but potentially valuable areas is more complex. The absence of protected status does not necessarily imply low biodiversity value; many internationally important biodiversity areas lie outside protected zones. Mining companies face the challenge of assessing the importance without clear protective designations and, hence, compliance requirements, using various criteria to determine local, regional, national, or international significance. Common evaluation criteria include:

- *Species/habitat richness:* A more diverse habitat or species variety may indicate a higher value. Habitat mosaics can be particularly valuable.
- *Species endemism:* Endemic species, which have evolved distinct characteristics due to isolation, are highly significant.
- *Keystone species:* Species that have a significant impact on ecosystems relative to their abundance, such as predators that control prey populations or other keystones species that transfer nutrients between ecosystems (ICMM, 2006).
- *Rarity:* Applies to ecosystems, habitats, and species, indicating susceptibility to extinction. However, Local biodiversity trends over time are likely to be decoupled from global trends, as local processes may compensate or counteract global change (Pilotto et mult.al., 2020). Thus, rarity at a local scale may not be reflected at national or global scale.
- *Size of habitat:* Larger areas are more viable and resilient, with higher habitat connectivity being beneficial; in addition to the various ecosystem services discussed above, small ecosystems can also be important stepping stones for species migrating between different habitats (which is one of the functions of RAMSAR sites).
- *Population size:* Significant for species conservation, especially for large predators needing extensive home ranges;
- *Fragility:* Sensitivity and resilience of ecosystems to changes;
- *Value of ecosystem services:* Recognizing the critical importance of services provided by ecosystems.

Despite the lack of universal standards, these groups of criteria help guide the assessment of biodiversity importance.

After identifying and evaluating potential environmental impacts, mining projects must implement a hierarchy of protective measures. These can be broadly categorised into three main approaches, each serving different but complementary purposes:

1. *Mitigation* has to implement measures to protect biodiversity and local populations from adverse mining impacts, identified through environmental assessments or as part of the operational or monitoring activities of mining companies. The goal is to prevent or limit these impacts to acceptable levels.
2. *Rehabilitation* aims to return mining-affected land to agreed post-closure functions and uses, focusing on identifying post-closure land uses that maximise the benefits for biodiversity and that have the support of key stakeholders.
3. *Biodiversity enhancement* seeks to improve biodiversity beyond mitigation or rehabilitation, addressing external threats, institutional shortcomings, or lack of scientific knowledge. However, our understanding of ecosystem functioning is usually rather limited in depth, so any 'improvement' can also have unforeseen and possibly unwanted consequences.

It should be stressed that mitigation measures have to be based on appropriate scientific and technical studies and need to be subject to extensive consultation with the competent regulatory authorities, the local population and other stakeholders. Key strategies in selecting mitigation measures include:

- *Avoiding impacts:* Preventing hazards, risk, and, hence, impacts at source is always a preferred option over mitigating consequences. Thus, already at the planning stages operations can be designed to prevent or limit impacts by e.g. choosing appropriate locations, process with lower risk potential, mining methods with less extractive waste and surface footprint etc. (see discussions below).
- *Minimizing impacts:* Implement actions to reduce impacts, such as advanced effluent treatment to protect aquatic biodiversity.
- *Rectifying impacts:* Rehabilitation of affected environments, attempting to recreate habitats and re-instituting (of possible) original or new, most beneficial land uses are after the fact treatments that should be the last resort, but sometimes are unavoidable.
- *Compensating for impacts:* Depending on the properties and functions of the impaired environments or habitats, it may be possible to offer substitutes at a different location. There are examples for a successful transfer of nesting locations for birds or compensatory reforestation, but the success is not always predictable and requires the availability of suitable land, the uses of which in consequence is also altered.

In summary, avoidance is always the preferred strategy, followed by measures to minimise impacts, then corrective actions, and finally, compensating for unavoidable impacts. Rehabilitation, while appealing as a concept, can have mixed successes due to a lack of sufficient systemic understanding, often can be more challenging and time-consuming than protecting the existing habitats and ecosystems in the first place.

Monitoring: A key element in risk and impact management is monitoring. The purpose of monitoring is to detect unwanted and undesirable changes and impacts early, to trigger corrective actions and to assess the efficacy of mitigation and rehabilitation measures over time. Monitoring involves thus collecting information to assess progress against biodiversity objectives.

However, biodiversity at a site is not easy to quantify, as it is an expression of numerous interacting components with different roles and function that may also change over time and space. The monitoring framework must be adapted to capture the diversity and changes. Hence, it is often not sufficient to monitor individual species, but one needs to look at groups of species, as the overall state of an ecosystem may not be compromised, although an individual species may decline (temporarily). Certain species may take on the role of another species, thus filling ecological niches.

Indicators can help to condense complex information, but selecting effective indicators is challenging due to the complexity and dynamics of natural systems. Indicators are usually key variables, such as pH in waters, have to be relatively easy to measure, and must be representative for the overall state of the habitat or ecosystems. Remote sensing can be an ideal tool to obtain quickly and cost-effectively data. For instance, UV reflectance can be measured using satellite- or air-borne sensors and gives a quick overview over the health of the plant coverage and stress factors, such as water or nutrient stress (e.g. Cravo and Guerreiro, 2019; see also Njambi, 2022, for an introduction).

Indicators must also resonate with institutional (i.e. regulators) and public stakeholders to be useful (Falck & Spangenberg, 2014). They are case-specific for each mining operation and must be selected, based on the identified nature values, in collaboration between the operator, the regulator and the general public. Key considerations for selecting and measuring indicators include: ecosystem, habitat, or species recovery ability; local value and role of biodiversity; interactions with natural processes; global, national, or local significance of biodiversity.

Indicators can be categorised as condition indicators, pressure indicators and response indicators. In fact, he DPSIR-framework (Driving forces, Pressures, State, Impact, Responses) is used to analyse and communicate environmental issues (EEA, https://www.eea.europa.eu/, see also Section 7.1). This framework helps understand the driving forces (such as population growth and changes in consumption and production patterns), environmental pressures (such as CO_2 emissions and land use), the state of the environment (such as air quality and natural resources), impacts (such as climate change and biodiversity loss), and societal responses (such as environmental policies and clean technologies).

Environmental indicators are chosen to reflect all these elements and their interactions. The relationships between pressures and the state of the environment highlight these relationships and help to predict impacts. Policy effectiveness indicators assess the impacts of environmental measures taken. The DPSIR framework, although often represented as a linear chain or a circle, is actually a complex web of interacting and recursive factors, with non-linear dynamics and operating at different geographical scales. This dynamic and interconnected framework helps policymakers address environmental issues effectively at different stages of the policy cycle (Gabrielsen and Bosch, 2003).

Verification: In order to verify the implementation of the environmental management plan, usually a follow-up audit is undertaken. Such audit in the mining sector covers estimating the impacts of existing extractive activities, identifying and evaluating any remaining environmental and health risks, and a general check, whether compliance with the applicable regulatory requirements has been achieved.

Stakeholder Involvement: As noted above, throughout all the process, stakeholders need to be actively involved, which will include local communities, government and multilateral institutions, investors and insurers, conservation NGOs and academic institutions, employees. Engaging these stakeholders is crucial for ensuring that rehabilitation solutions and possible restrictions on land use meet their expectations. Building trust, respect, and partnerships with the community ensures sustainable projects. Stakeholders often have diverse and conflicting interests in nature conservation, and reconciling these differences is essential. Stakeholder engagement helps understand the impacts of mining operations beyond a purely scientific-technical understanding and develop mitigation measures that meet their expectation. It has to be built on respecting local cultures, engaging communities, and fostering in their social and economic development. Guidance on stakeholder engagement in a European context can be found in Tost et al. (2021).

Finally, the Environmental Management System framework proposed by ICMM (2006) guides mining companies in addressing biodiversity by integrating it into their environmental policy, documenting local biodiversity, assessing biodiversity risks, maintaining legal compliance, planning preventative and mitigative measures, implementing responses, monitoring performance, and continuously improving. Clear goals and objectives for biodiversity management are crucial, set in consultation with stakeholders like local communities, regulators, and academics. Objectives can be specific, such as reintroducing key species or protecting migration patterns, and should align with biodiversity values. Actions to achieve these objectives are documented within the EMS, with specific targets set for each operation, considering resources, technical constraints, community engagement, and long-term land management requirements.

2.3 Assigning levels of protection and sensitivity

Assigning levels of protection and sensitivity to the environment in the context of mining activities has to be based on assessments of the environmental value and vulnerability of specific areas and ecosystems as detailed above. This process helps to determine the level of environmental protection measures and mitigation strategies that need to be implemented to minimise the impact of mining on the environment.

Here are some steps to assign levels of protection and sensitivity to the environment in relation to mining activities:

Classify protection levels: Classifying the identified areas and ecosystems based on their level of protection and sensitivity to environmental impacts. This can be done using a tiered approach, such as assigning different levels of protection (e.g., high, medium, low) based on the ecological significance, species diversity, habitat integrity, and vulnerability to disturbance. As touched upon earlier, IUCN (Dudley, 2008) distinguishes different levels of protection needs into seven categories (Table 1). According to other UN conventions, to EU Directives and national legislation, there are other types and categories of protection, which partially overlap with the IUCN categories.

Table 1: Categories of protection according to IUCN (Dudley, 2008).

Cat.	Name	Description
Ia	Strict nature reserve	Strictly protected for biodiversity and also possibly geological/geomorpho-logical features, where human visitation, use and impacts are controlled and limited to ensure protection of the conservation values
Ib	Wilderness area	Usually, large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, protected and managed to preserve their natural condition.
II	National parks	Large natural or near-natural areas protecting large-scale ecological processes with characteristic species and ecosystems, which also have environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.
III	Natural monument or feature	Areas set aside to protect a specific natural monument, which can be a landform, sea mount, marine cavern, geological feature such as a cave, or a living feature such as an ancient grove.
IV	Habitat/species management area	Areas to protect particular species or habitats, where management reflects this priority. Many will need regular, active interventions to meet the needs of particular species or habitats, but this is not a requirement of the category.
V	Protected landscape or seascape	Where the interaction of people and nature over time has produced a distinct character with significant ecological, biological, cultural and scenic value: and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values.
VI	Protected areas with sustainable use of natural resources	Areas which conserve ecosystems, together with associated cultural values and traditional natural resource management systems. Generally large, mainly in a natural condition, with a proportion under sustainable natural resource management and where low-level non-industrial natural resource use compatible with nature conservation is seen as one of the main aims.

Areas of potential land use conflicts: Stolton et al. (2013, in Dudley, 2008) provide guidance on areas to be considered for protection, which in turn helps to identify areas where in the future land use conflicts may arise. There is a growing focus on areas that demonstrate high biodiversity value and their potential to provide vital ecosystem services. Member States are asked to prioritise such areas, aligning with the objectives set out for enhancing ecological resilience in the face of climate change. Ecosystems that exhibit pristine conditions or play critical roles in ecological connectivity, such as migratory bird habitats, merit particular consideration for strict protection. To ensure the effectiveness of strict protections, designated areas must have clearly defined conservation objectives. The overall aim is to minimise human interference, allowing natural processes to thrive. Management interventions should be limited to those that are indispensable for maintaining natural processes, such as control of invasive species or measures to prevent wildfires. Each area will require tailored management plans that specify compatible activities and outline regulatory controls to safeguard ecological integrity. Regular assessments will be necessary to ensure that authorised activities align with conservation objectives and the unique ecological needs of the area. Strictly protected areas should have legal backing, meeting the same overarching criteria applied to all protected areas. Such areas may be fully protected zones or parts of broader protected landscapes, including Natura 2000 sites or those under national protection schemes. Legal instruments for designation may include national laws, long-term agreements, or zoning in broader area management plans, necessitating clear identification within such frameworks. The coordination process for strictly protected areas mirrors that of broader protected areas under the 30% target. Member States should proportionately contribute to achieving the strategy’s targets based on the natural values within their jurisdictions that require strict protection and restoration potential. The same monitoring principles apply to strictly protected areas, ensuring a unified approach to tracking progress. The Central Database on Designated Areas (CDDA) includes information relevant to monitoring and evaluating adherence to the strict protection objectives (and allows to identify potential land use conflicts, see Ovaskainen et al., 2024). The strategic aim is to establish a coherent Trans-European Nature Network that effectively integrates ecological corridors, thereby supporting the protection of at least 30% of EU land and sea areas. The Natura 2000 network provides a foundational framework for this endeavour, with efforts focused on improving ecological coherence through landscape management that facilitates wildlife migration and genetic exchange. Recognising the importance of ecological corridors is vital to the integrity of the protected areas network. These corridors enable species migration, enhance resilience to climate change, and help maintain ecosystems. Member States should ensure that their designations also account for these corridors, which may not individually qualify as protected areas but play essential roles in fostering connectivity. Urban and peri-urban areas represent critical components of the ecological network, enhancing connectivity and providing ecosystem services. While legal protection may not always be feasible, these areas should still be integrated into the broader ecological corridors strategy, contributing to the overall resilience and coherence of the Trans-European Nature Network. Efforts to green cities must be approached strategically to maximise their ecological and societal benefits.

It should be noted that the above requirements formulated by Stolton et al. (2013), while mentioning societal benefits, do not seem to acknowledge the societal needs for mineral raw materials.

Establish buffer zones and exclusion zones: Create buffer zones and exclusion zones around environmentally sensitive areas to minimise the direct impact of mining activities. Buffer zones can act as protective barriers to reduce pollution, noise, and disturbances, while exclusion zones restrict access and prevent any mining activities within designated areas.

Implement conservation measures: Develop and implement conservation measures and best management practices to safeguard environmentally sensitive areas and mitigate the impacts of mining. This may include reforestation, habitat restoration, erosion control, water management, and pollution prevention measures.

Monitor and enforce compliance: Establish monitoring programmes to track environmental changes and assess the effectiveness of protection measures. Enforce regulations, permits, and environmental guidelines to ensure compliance with environmental standards and protect sensitive ecosystems from harm. The EU Earth Observation Programme (COPERNICUS, https://www.copernicus.eu/) provides tools and infrastructure for remote monitoring.

Engage stakeholders and local communities: Involve local communities, indigenous groups, the general public, and environmental organisations in decision-making processes and conservation efforts. This can help build support for environmental protection initiatives, promote sustainable land use practices, and foster stewardship of natural resources.

Spatial data management: The INSPIRE Directive (CEU, 2007) aims to establish a European Union Spatial Data Infrastructure (SDI) to support EU environmental policies and activities impacting the environment. This infrastructure facilitates the sharing of environmental spatial information among public sector organisations, enhance public access to spatial information across Europe, and aid in cross-border policy-making. It relies on spatial information infrastructures set up and managed by EU Member States. Today it covers a wide range spatial data themes and an up-to-date list can found at: https://knowledge-base.inspire.ec.europa.eu/tools/inspire-themes_en. Annex III themes of relevance here include inter alia:

- Area management / restriction / regulation zones & reporting units: https://knowledge-base.inspire.ec.europa.eu/area-management-restriction-regulation-zones-reporting-units_en
- Land use: https://knowledge-base.inspire.ec.europa.eu/land-use_en, and
- Mineral resources: https://knowledge-base.inspire.ec.europa.eu/mineral-resources_en

By systematically assessing the environmental value and vulnerability of specific areas, assigning appropriate levels of protection, and implementing targeted conservation measures, mining activities can be managed in a way that minimises environmental impact and preserves the integrity of ecosystems for future generations.

3 Geological factors influencing mining methods and impacts

3.1 Overview

Defining the characteristics of mineral deposits is a crucial aspect of ore geology, as it provides valuable information for exploration, mining, and resource evaluation. Understanding the key features of mineral deposits helps geologists assess the economic potential, mineralogy, grade, and distribution of ore bodies.

These characteristics of the mineral resource are also crucial for determining the most suitable mining technique and strategy that has the least environmental impact and surface footprint. It is obvious that shallow resources for geotechnical and economic reasons can only be exploited in open-cast mines, which normally are not compatible with protected areas. For deep resources a wide variety of mining techniques exist or are under development.

The characteristics outlined below are used to define mineral deposits in ore geology. It should be noted that much of the information can only be obtained from sampling the mineralisation, i.e. through invasive exploration.

Exploration indicators, signatures, and geophysical anomalies guide the initial mineral prospecting and exploration efforts. Exploration target criteria are defined on the basis of the characteristics of known mineral deposits, geological controls, and mineralisation models. The integration of geological, geophysical, geochemical, and remote sensing data help to identify prospective areas for further exploration and drilling.

Geological setting and host rock characteristics, including rock type, age, structure, and stratigraphy provide the overall framework for assessing a mineral resource. In detail this includes the identification of ore-bearing formations, mineralised zones, and geological environments conducive to mineralisation (e.g., magmatic, hydrothermal, sedimentary). Other information that helps the geologists in their assessments are the relationship to regional tectonic events, geological structures, and mineralisation processes that influence the formation and distribution of mineral deposits. This work also permits to assess

Shape, size, extent, and geometry of a mineral resource, including dimensions, orientations, and dip angles. Together with a classification of deposit types based on morphology (e.g., tabular, stratabound, stockwork, vein, breccia) the spatial relationship of the mineralisation with respect to protected areas at the surface, such as its likely depth and extent below the surface and its location with respect to the boundaries of the protected area can be determined.

Mineralogical composition of the deposit, that is the types of minerals present and their distribution within the ore body, based on an identification of primary ore minerals (e.g., chalcopyrite, sphalerite, galena) and associated minerals (e.g., gangue minerals, alteration minerals), as well as the determination of mineral associations, textures, and mineral paragenesis to understand the origin and formation of the deposit. These characteristics to a significant degree will determine how the ore can be processed in order to extract the metal value of interest. In turn, this will determine the possible environmental risk associated with these processes and also the disposal options for tailings and other process residues.

Chemical composition of the ore body, including major and trace elements, isotopic signatures, and elemental ratios. Geochemical signatures, anomalies, and patterns indicate the presence of ore minerals and potential mineralisation zones. Together with investigating any geochemical zoning, dispersion patterns, and alteration halos that reflect hydrothermal processes and mineralisation events they may allow to draw conclusions with respect the size and spatial extent of the resource.

Concentration of valuable minerals in the ore body, expressed as ore grade (e.g., percentage of metal content per ton of ore) together with the identification of ore shoots, high-grade zones, and ore bodies with economic potential for mining and an assessment of mineralisation styles (e.g., disseminated, vein-type, massive sulfide) and mineralisation controls (e.g., structural controls, lithological controls) allow to make decisions on the most appropriate mining, processing and in consequence extractive waste disposal strategies. From the available options the ones with lowest risk potentials and least probable impacts would need to be chosen.

By considering the above properties and characteristics, geologists can effectively define and evaluate mineral deposits, assess their economic potential, and optimise exploration and extraction strategies. This systematic approach helps in resource assessment, ore reserve estimation, and decision-making in the mining industry.

These investigations are typically summarised in a 3D-model of the mineral resource that will be continuously updated and refined as exploration and eventually exploitation progresses. Such 3D-models are today key instruments of mine-planning. Combined with other, e.g. GIS-based, spatial data representations they help to resolve planning conflicts and to assess potential impacts. They can also be valuable tools in stakeholder communication, demonstrating for instance the spatial separation in three-dimensions of mine operations and protected areas, where appropriate.

3.2 Materials properties

Characterisation of extracted materials: The initial characterisation will have to be based on drill-cores and -chippings, but need to be successively refined and confirmed as the excavation of the mine progresses. The characterisation saves both, economic and environmental protection purposes.

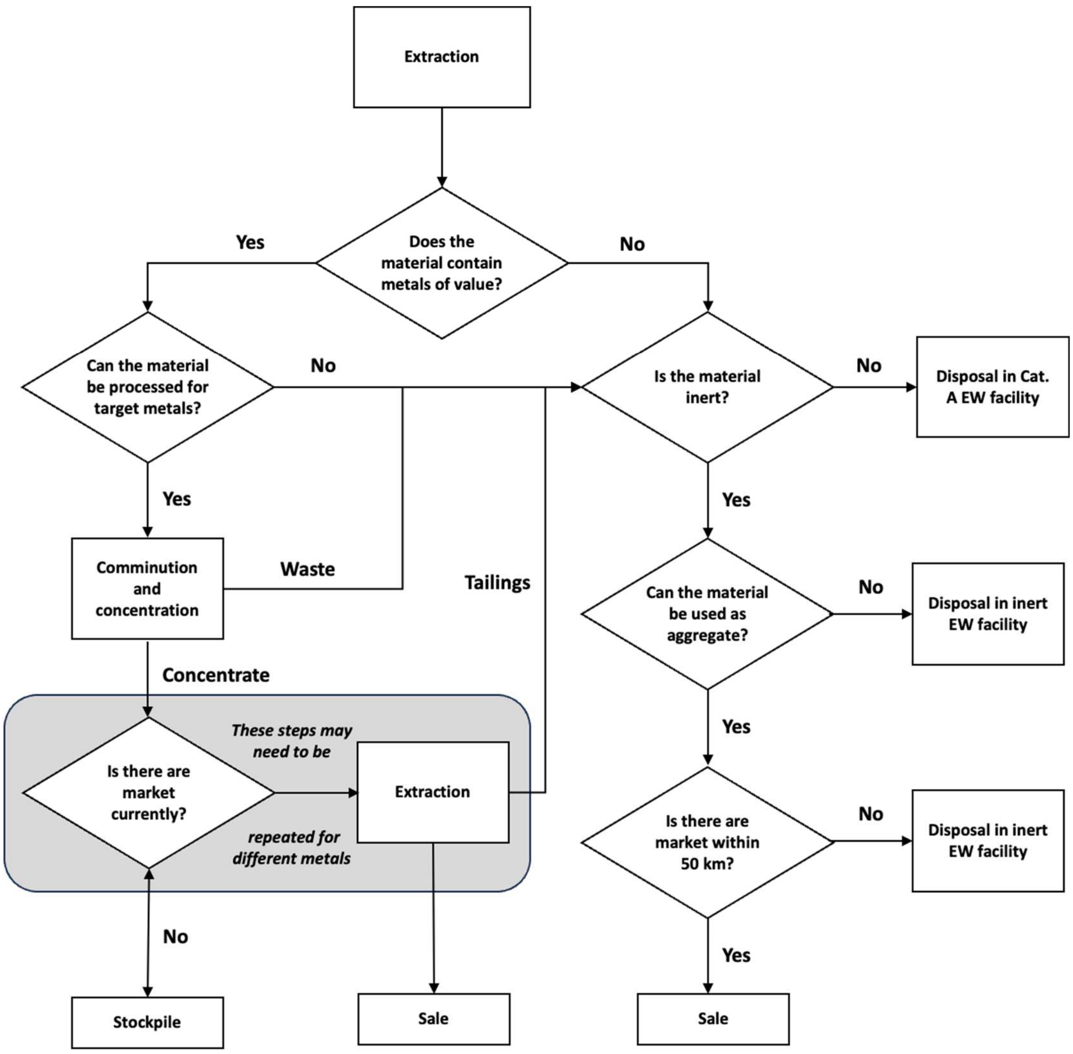

Figure 1: Conceptual decision tree for the valorisation of different types of extracted materials.

The environmental baseline assessment should start with a detailed characterisation of the geological environment, including resources of metallic minerals and the geological materials that make up the 'overburden' and gangue. Materials eventually considered waste must be managed according to the Extractive Waste Directive (EWD, 2006). This concerns in particular materials that can give rise to contaminated, acid, alkaline or saline mine and/or rock drainage. Parbhakar-Fox and Baumgartner (2023) underline that a comprehensive characterisation during the exploration and the actual mining phase help to make extractive waste management more efficient. As demanded by the EWD, the characterisation should also help to explore opportunities for marketing such materials (e.g. as additives or aggregate for construction purposes) or their re-use within the mine (e.g. for construction or back-filling). Such characterisation would then also include determining their geotechnical properties.

According to the CRM-Act (CRMA, 2024), all extracted materials should be screened for their total metal value and not only with respect to the original target metal in order to make extractive operations and conserve valuable resources. While this makes sense from a long-term strategic point of view, the practicalities of stockpiling mineral resources for which at a given moment no market exists remains unresolved. Figure 1 outlines a valorisation decision-making tree based on such characterisation of extracted materials.

Mineralogy and analysis of whole rocks – These are key elements of the characterisation of the materials to be extracted. Maest et al. (2005) provide guidance on the type of geochemical analysis that a mining project proponent must include to predict possible impacts on water quality, including the release of contaminants and acid drainage:

"The first step in characterizing extracted materials is to determine the geology and mineralogy of the rocks on the mining site. Such analysis includes determining the type of rock, alteration, primary and secondary mineralogy, availability of acid-producing and neutralizing minerals and minerals that release metals (e.g., veins, disseminated, encapsulated, etc.), and the positions and sizes of oxidised and non-oxidised zones for all types of waste, quarry walls, and underground workings.

"The next step in geochemical characterisation of extracted materials is to define geochemical test units. Geochemical test units are types of rock with distinct physical and chemical characteristics.

"Depending on the results of characterisation, some of the test units may be grouped together in the mining waste management plan. Alternatively, if an initial unit designation provides a wide range of test results, it may be necessary to subdivide the unit for waste management purposes...

"The third step in material extraction characterisation is to estimate volumes of each type of material to be generated and the distribution of material types in waste, quarry, and underground workings... Information about the geochemical test units should be coordinated with the mining waste management plan.

"The fourth step in characterisation involves running small-scale tests on the ore, which involves creating dump slag and/or heap leach materials in the laboratory... The general categories of geochemical tests that will be performed on geochemical test units are whole rock analysis, static tests, short-term leach tests, and kinetic tests."

3.3 Deposit size, shape, and depth

The deposit size, depth and shape are critical factors that determine the economically feasible mining techniques. These in turn determine, whether the deposit can be mined from underneath or within a protected areas with sufficiently low environmental impacts in both, the short and the long-term.

Mineralisations of economic interest occur in wide variety of geological settings. Given the intensive mining activities across Europe over the centuries, is rather likely that most mineralisation near the surface have already been exploited. On the other hand, there are many target minerals of interest today that were not of interest in the past and, hence have been overlooked. In CIRAN deliverable D3.2 (Ovaskainen et al., 2024; cf. Figure 2 below) an attempt was made to map the likely coincidence of mineralisations of interest with currently protected areas.

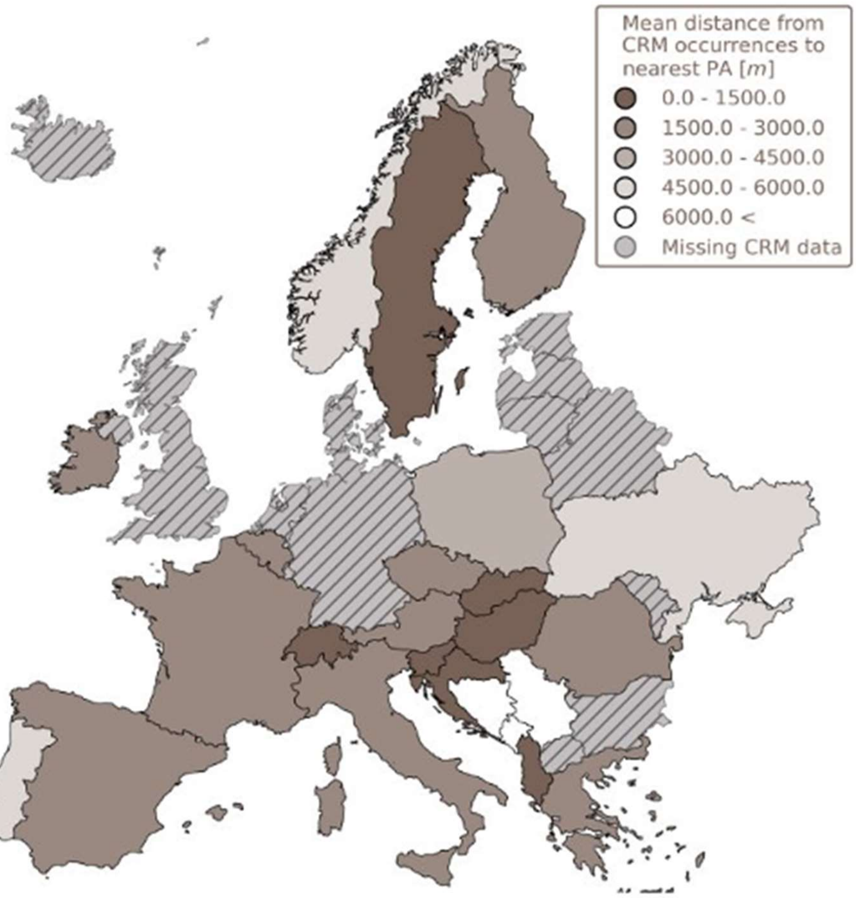

Figure 2: Mean Distance (km) from CRM Occurrence to nearest Protected Area
(Source: Ovaskainen et al., 2024).

Before any drilling has been undertaken, our knowledge of the geology at depth is based on extrapolations of surface mapping, on geophysical investigations that only provide indirect information and on extrapolations from existing mine works, if there are any. Ground-truthing of geophysical investigations by drilling boreholes is possible, but costly and only undertaken when deemed promising. As discussed in Section 4.1.1 exploration already can have some environmental impacts, but exploration can be designed to minimise both, short- and long-term impacts.

The topology of the mineralisations and the structure of the surrounding rocks will determine, how these mineralisations can be accessed effectively and efficiently.

Depth: The deeper a mineralisation occurs below the surface, the less likely a mine is to impact a protected area on the surface. However, a mine requires surface installations and space for the management of extractive wastes. With increasing depth, the stripping ratios, i.e. the amount of rock that needs to be removed in order to provide access to the actual target mineralisation increases unfavourably. The deeper the mineralisation the longer the shafts or inclines for transporting the excavated material to the surface have to be. In consequence more material has to be moved during the construction of the mine. As these excavated materials come from shafts, tunnels, etc. that provide access to the actual mineralisation, there are not yet any mined-out areas in which these materials can be used as backfill. Thus, they have to be managed at the surface, if no use, e.g. as aggregate, outside the mine can be found.

Size: The expected overall size of the mineralisation, based on the exploration results, will determine the scale of the operation and how long it is expected to last. This also then determines the amount of extractive waste that will have to be managed. The overall environmental impact is likely to be proportionate to the size of the mineralisation that will be exploited.

Shape: The type of mineralisation (stratiform, vein-type, etc.), its extent in 3D-space (horizontal, vertical), and its relation to geological features (e.g. fractures) will have significant influence on the mining method and technology that can be used. It also determines the ratio between gangue and ore and hence the amount of waste to be managed. In turn it also determines, how much of the extractive waste can be managed underground and what technique can be used for that.

3.4 Rock types and structures

The structure and properties of the host rock are important to understand the ore formation processes, which in turn determine the shape of the mineralisation. With the aid of this information, the exploration geologist can assess the likely topology of the mineralisation (cf. Section 3.3). The properties of the host rock and the properties of the surrounding rocks will significantly determine which kind of mining technology and strategy can be used. Crystalline rocks, such as granites, will require a different mining method compared to, for instance, sandstones. The kind of fracturing, its frequency and orientation are also important variables.

Rock permeabilities and the fracturing will determine the presence and flow of groundwaters in the host rock and, hence, what kind of water management will be required. The presence of aquifers and less permeable zones and horizons together with the water management measures needed to keep the mine dry determine the determine the depression cone that develops and hence the ensuing potential environmental impacts.

To some degree the relevant information can be inferred from a synthesis of information collected from geophysical, geological, geochemical investigations and stream-water sampling during exploration, but would need to be corroborated by drilling. Other, already existing nearby mines will provide further insights. Drilling will be required to verify the deposit as economically viable eventually.

Ore Formation: Rock permeability, porosity, and fluid pathways in the geological past have controlled the migration and precipitation of ore-forming elements in fluids. The presence of fractures, faults, and permeable zones in otherwise impermeable rocks can enhance mineral deposition.

Host rock characteristics such as lithology, alterations, and mineral assemblages can indicate the type of mineralizing events (e.g., magmatic, hydrothermal, sedimentary) and help interpret the genesis of the deposit.

The structural properties of the host rock, such as folding, faulting, and shear-zones, can create favourable conditions for mineralisation. Such structures control the geometry, orientation, and continuity of ore bodies.

Lithological variations and bedding characteristics can influence ore grade distribution, ore shoot formation, and mineralisation style (e.g., disseminated, vein-type, stratiform).

Understanding the relationship between host rock properties and ore grade variations helps in delineating high-grade zones, optimizing mining methods, and resource estimation.

Geophysical Signatures: Rock properties affect the geophysical response and signatures of mineral deposits, influencing exploration targeting and detection methods. Certain rock types exhibit distinct geophysical anomalies (gravimetric, electrical conductivity) that indicate the presence of mineralisation.

Geophysical surveys, such as electromagnetic, magnetic, electro-telluric, and gravity methods, are sensitive to variations in rock properties, allowing the identification of structural discontinuities and changes in lithology, which in turn indicate prospective areas for mineral exploration.

Integration of rock property data with geophysical and geochemical signatures (cf. Section 3.5) helps in refining exploration targets, targeting mineralised zones, and prioritizing drilling locations.

Mine Planning and Rock Mechanics: Rock properties determine the stability, strength, and geo-mechanical behaviour of the rock masses underground. Understanding rock mechanics is crucial for safe and efficient mine excavation and ore extraction.

Variations in rock properties, such as in compressive strength, abrasiveness, and bulk stability, impact excavation methods, tunnelling techniques, and ground support design in mining operations.

Assessing rock properties in the surrounding environment helps in predicting potential geotechnical hazards, such as rockfalls, roof collapse, outbursts, subsidence, and ground stability issues that can affect mine safety and productivity.

In summary, the rock properties of the host rock and surrounding rock play a pivotal role in all stages of mineral exploration, mine design, and mine-operations. By characterising and understanding these rock properties, geologists and mining professionals can better interpret mineralisation processes, target prospective areas for exploration, optimise ore extraction and extractive waste management methods, and mitigate geotechnical risks in mining activities.

3.5 Rock and ore geochemistry

While the structure of the host rocks can give indications as to the likely location of ore formation, the mineralogy and its geochemical composition can provide valuable insights into the origin, evolution, and processes of mineralisation. Certain geochemical signatures and elements may indicate the type of mineralising event (e.g., magmatic, hydrothermal, sedimentary) that led to ore formation, which in turn may give indications of the shape and size of the ore body.

Geochemical anomalies, patterns, and associations in the host rock can reveal the presence of ore-forming elements, their sources, pathways, and enrichment processes that led to the concentration of valuable minerals.

Elemental ratios, isotopic signatures, and mineralogical associations in the host rock can help understand the geochemical controls and conditions that favoured mineral deposition and ore enrichment.

It should be noted that the investigations detailed below are standard procedures in any kind of exploration project. However, a very detailed exploration will help to decide in an early stage of the project, whether exploitation will be compatible with the surface status of a protected area. While also needed from a potential investors' perspective, one has to be confident that the potential impacts from constructing a mine can be justified with a supply of critical raw materials.

Exploration Indicators and Targeting Criteria: Geochemical anomalies and signatures in the host rock act as exploration indicators and targeting criteria for mineral exploration. Elevated levels of certain elements or minerals in the rock may indicate proximal mineralisation or prospective ore bodies, particularly, when related to the structural assessment.

Geochemical surveys, including soil and rock sampling, and geochemical mapping, can be used to identify geochemical anomalies and dispersion patterns that guide exploration efforts to potential mineralised zones.

Integration of geochemical data with geological, geophysical, and remote sensing data helps in in refining exploration targets, prioritising drill locations, and delineating mineralised areas for further investigation.

Ore Grade and Mineralisation Zoning: Geochemical analyses of the host rock can help in determining the grade, distribution, and mineralisation zoning of ore bodies. Geochemical studies can identify high-grade zones, ore shoots, and metal enrichment patterns that influence resource estimation and mine planning.

Element geochemistry can be used to calculate geochemical proxies for ore grade estimation, such as metal ratios, alteration indices, or geochemical vectors that correlate with mineralisation intensity and economic potential.

Geochemical modelling and interpretation of geochemical anomalies help in understanding the lateral and vertical variations in ore grade, mineralogy, and metal content within the mineralised system.

Alterations and Pathfinder Minerals: Geochemical studies of alteration minerals in the host rock provide important clues about the hydrothermal alteration processes associated with mineralisation. Alteration minerals thus can serve as pathfinder indicators for ore deposits and guide exploration efforts.

Geochemical characterisation of pathfinder minerals, such as pyrite, arsenopyrite, sericite, and chlorite, can help in tracing mineralising fluids, predicting mineralisation styles, and identifying alteration halos that lead to ore bodies.

Geochemical analysis of trace elements, including base metals, precious metals, and rare earth elements, helps in mapping alteration zones, identifying geochemical anomalies, and delineating target areas for mineral exploration.

Overall, the geochemical aspects of the host rock in which mineralisations are found are crucial for understanding the genesis, distribution, and controls of ore deposits, and hence their shape and potential extent. By analysing the geochemical composition of the host rock, geologists can interpret mineralisation processes, target prospective mineralised zones, estimate ore grade, and advance mineral exploration and development efforts.

3.6 Groundwater

Groundwater compositions are a reflection of the rock/water interactions and the residence times of the groundwaters. The presence of certain (trace) metals may reflect the presence of mineralisations of interest. The isotopic composition of groundwaters allows conclusion about the residence times and the speed with which the groundwater moves naturally through the host rocks, which is important for judging whether and how quickly a deep mine might impact near-surface water bodies. The groundwaters are also important carriers for contaminants arising from mine-operations. A mine will disturb the natural hydro- and geochemical environment in the area of mining. Thus, the introduction of atmospheric air at the contact between the rock and open mine works will lead to the oxidation of minerals (specifically sulfidic ones) and give rise to acid mine-drainage. In turn, the acid drainage can dissolve other minerals which may contain compounds that are considered toxic.

As noted above, deep mining almost certainly will take place below the local and regional groundwater levels. Depending on the host rock properties and structure, inflowing and infiltrating groundwater will have to be managed in order to keep the mine dry and workable. This in turn will influence the mining methods and strategy. Understanding and managing groundwater is crucial for mine planning, design, and operations to ensure the safety of personnel, the stability of mine workings, and the protection of the environment.

Dewatering and Water Management: The water entering into open mine workings underground has to constantly removed to maintain dry working conditions. In fact, the process of dewatering the area in which the future mine will have to begin before the actual construction of the mine can begin. This large-scale dewatering will result in a groundwater depression cone and increased flow-rates in open faults and permeable water bearing strata.

Mining methods, such as sublevel caving, block caving, or open-pit mining, may require specific dewatering systems, including groundwater pumping, drainage tunnels, sumps, and wells to control groundwater inflows and manage water levels within the mine workings. It should be noted that novel mining techniques are currently being developed, involving robots that can work below the water table, thus reducing the need for dewatering.

Pumps for water management are installed at the lowest point of the mine, the sump. The sump collects all drainage waters from within the mine. Due to the mine operation, the sump waters may be contaminated with oils, explosives residues, and may be acidic. They always require treatment before discharge.

Depending on the overall hydrogeology of the site and its surroundings the groundwater depression cone may affect near surface aquifers and thus the ecosystems at surface. Surface water courses may dry out, plants may not reach anymore with their roots the groundwater, drinking-water may fall dry, etc.

Sealing of shafts etc. that penetrate water-bearing strata, lining/grouting of adits, tunnels etc. and sealing faults and fractures again water ingress reduces the amount of water that needs to be managed. Likewise, backfilling and damming up worked out mine areas reduces the surface through which groundwaters can enter the mine.

Proper water management is essential to prevent water-related hazards, such as outbursts, roof collapses, slope instability, and inundation of working areas, which can disrupt mining operations, increase safety risks, and can impact mine-operations.

Water management in extractive wastes: It needs to be noted that groundwater tables will also develop in spoil heaps. As the rocks disposed in them will not be in equilibrium with the surface conditions, it is likely that certain minerals, such as sulfides, are not stable and will oxidise, which gives rise to acid rock drainage. Covering such heaps with impermeable layers and (re)vegetation will reduce the water inflow and thus the driving forces behind acid rock drainage. Nevertheless, spoil heaps will need to be drained and the drainage collected for treatment and discharge.

Tailings ponds, by definition contain large amounts water (see Figure 3), though modern paste technology aims to reduce this right from the beginning, mainly with dam safety in mind (Global Tailings Review, 2020). Tailings ponds need to be covered and (re)vegetated as soon as geotechnically possible. As tailings pond are often located in valleys for conveniences sake, surface water diversion channels need to be built in order to reduce the water inflow into the ponds. Modern tailings ponds are always constructed with impermeable bottom layers and drainage collection systems. The drainage needs to be treated before discharge.

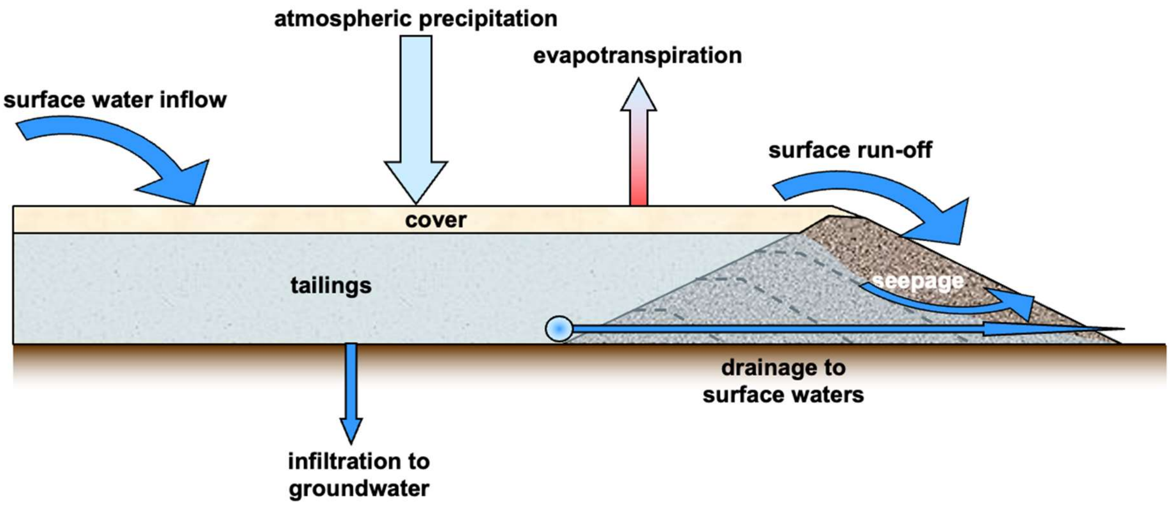

Figure 3: Water balance in a tailings pond.

Ground Stability and Geotechnical Risks: Groundwater conditions can influence the stability and deformation behaviour of rock masses in mines. High groundwater pressures can increase porewater pressures in the rock mass, leading to reduced rock strength, slope failures, and ground instability. Thus, mining methods and excavation techniques need to account for groundwater effects on geotechnical stability, ground support requirements, and excavation design parameters. Groundwater control measures, such as grouting, pre-drainage, and ground reinforcement, may be implemented to manage geotechnical risks associated with water saturation. As noted in the preceding section, they also reduce the amount of water to be managed.

Monitoring of groundwater levels, piezometric data, and geotechnical instrumentation is essential for assessing ground conditions, identifying potential hazards, and implementing mitigative measures to ensure safe and stable mining operations. A stable and well-managed mine will also have less impact on the environment.

Solution mining: *In situ* leaching (ISL, see Section 4.3) can be applied to ore minerals that can be dissolved in strong acids or alkaline solutions (notably certain copper and uranium minerals). It always takes place below the groundwater table. While during operation a suitable arrangement of injection and extraction wells together with a screen of protective well ensure an inward groundwater gradient, after the end of operations, residual acids or alkaline leaching solutions may give rise to a dispersion of contamination, which needs to be managed appropriately. However, due to the mineralisation and naturally high concentrations of constituents that normally would be considered contaminants, waters from such zones would only be useable after appropriate treatment.

Environmental Impacts and Water Quality: Mine drainage waters are commonly discharged into surface water courses, which changes their annual and seasonal flow patterns and consequently the aquatic ecosystems. Some jurisdictions may allow re-injection of drainage waters into aquifers, while others do not. In any case, drainage waters from mines and extractive waste management facilities most likely will require treatment before release to remove contaminants accumulated in the sump and to adjust pH. This helps to reduce impacts on the aquatic ecosystems and helps to maintain the surface waters as a natural resource.

Regulatory compliance is normally ensured through environmental and water monitoring programmes, carried out by both, the operators themselves and the respective executive arms of the regulatory authorities. The regulatory authorities will also set the quality requirements and permissible quantities for discharges.

In the EU, the Water Framework Directive (CEU, 2000) provides the overall regulation with respect to protecting this natural resource. National legislation transposes it and provides more detailed regulations and guidance.

Many mine operations, particularly those in conjunction with processing facilities will aim to recycle as much of their process waters and re-use drainage water for this purpose as possible, thus reducing the water strain in the area and limit the amounts to be discharged.

Hydrogeological considerations in mine-planning: It follows from the above, that hydrogeological investigations are critical in mine planning and design to characterise groundwater conditions, assess water balances, and develop appropriate strategies for (ground)water management. Understanding hydrogeological parameters, such as aquifer topologies, permeabilities, hydraulic conductivity, water-bearing faults and fractures, groundwater flow patterns, and recharge rates, is essential for building a hydrologic model to assess the impact of a planned mine onto the regional hydrology and design a mine water management system that not only optimises the mine dewatering with respect to operations, but also with respect to minimise the impact of the mine on the regional hydrology and in consequence ecosystems. This model should be able to predict the evolution of the hydrology along the entire life-cycle of the mine and in consequence needs to be able to be adapted to the real mine situations this evolves.

Climate change: The already noticeable changes in climatic conditions and weather patterns have an impact on groundwater recharge rates and surface water flows. Mine planning has to take into consideration that past hydrological observations may not provide an adequate basis anymore for designing mine water management. The capacity of storm-water management systems may need to be increased in order to account for higher rainfall intensities and lower groundwater recharge rates will exacerbate the effects of draw-down due the dewatering of a mine. Conversely, some areas across Europe may face increasing water stress and mine-related draw-down would add to this. Such water-shortage can also put constraints on mine operations that require process water.

In summary, one may note that groundwater conditions significantly influence mining methods and impacts. Effective management of groundwaters is essential for ensuring the safety, efficiency, and sustainability of mining operations. One must not forget also the potential mining-induced impacts on surface water courses and wetland. Collaboration between hydrologists, hydrogeologists, geotechnical engineers, mining professionals, and ecologists is key to addressing groundwater challenges and implementing solutions that optimise mining practices and mitigate potential risks associated with water management in mining operations.

4 Mining processes and technologies

4.1 Overview of mining risks

Any extractive operation, regardless how well it is planned and executed will have some environmental and possibly also societal impacts. There is always room for improvement and the purpose of CIRAN *inter alia* was to explore where and how extractive operations could be made more benign with a view to reduce short- and long-term impacts. It is helpful to first review the type of risks and impacts are typically associated with extractive operations. The focus is on environmental, but also on societal impacts, while risks to the operators and their personnel - operational health & safety (OHS) risks are of lesser importance for the purpose of this project. It is, however, acknowledged that often reducing OHS risks can also reduce environmental risks, due to better work practices and an improved safety culture, which reduce incidents that may have an effect on the environment.

For the purpose of the guidance on risk management in the extractive industry (Eco-Efficiency et al., 2024) developed on behalf of the European Commission's DG Environment a comprehensive catalogue of risks associated with all phases of a mine life-cycle (cf. Figure 4) and the associated processing has been developed. In the following, a brief overview over this risk catalogue will be given, which in turn serves as guidance for assessing, where technologies reviewed have the potential for significant risk reduction.

It needs to be kept in mind that optimisation of risk reduction for one phase of the life-cycle or for one particular aspect may be counterproductive. Risk reduction has to be systemic and include all dimensions of an extractive operation, including the dimension of time. The latter is important, because something that effects a short-term risk reduction in fact can cause elevated risks later on in the life-cycle.

Basis for risk assessment here are the *Guidelines for Risk Assessment in the Extractive Industries* recently developed on behalf of DG ENV (Eco-Efficiency et al., 2023). These guidelines include a comprehensive catalogue of environmental and OSH risks. Pertinent EU regulations and directives (cf. Section 3.3) were also be taken into consideration.

The cited Guidelines cover four main Focus Areas (FAs) that reflect elements of the life-cycles of extractive operations:

FA1 – Exploration

FA2 – Project planning and development incl. mine construction

FA3 – Underground and Surface extraction incl. processing

FA4 – Closure, remediation and long-term management

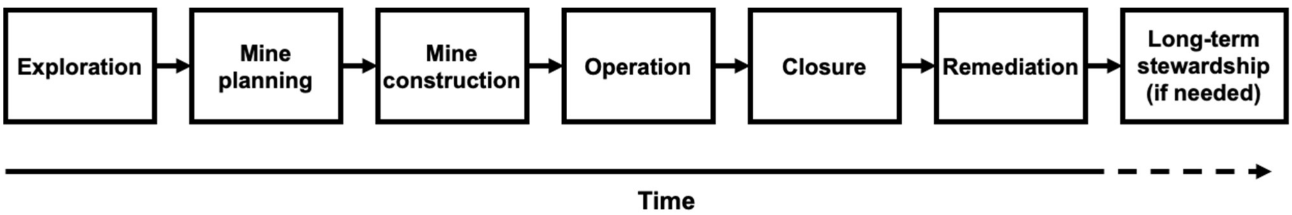

Figure 4: Outline of the mine life-cycle.

A key conceptual approach in all risk assessment is the 'source – pathway – receptor' paradigm (Figure 5), or in other words:

What is the cause of the risk? – how can it cause harm? – who or what can be affected?

Risk management can address any of the three elements, but the preference is for treating the source, then if the first is not feasible, the pathway. Removing receptors, for instance, preventing the access of the public to zones (potentially) at risk, typically is the last resort. However, (temporary) receptor removal is a typical risk management method in a technical context by e.g. limiting the amount of time an employee can spend in higher risk parts of a plant, fencing off certain areas, guard rails, etc. The discussions in the following section can all be conceptually seen in this way.

Figure 5: The Source-Pathway-Receptor model in risk management.

4.1.1 Exploration

Exploration activities have specific environmental and operational health & safety (OHS) risks associated with them, but at the same time allow to establish the baseline for environmental impact assessments (EIAs) and for planning the future safe operation of combined extraction. Exploration activities may include the following:

- Remote / desktop studies prior to entering the field to undertake Exploration;
- Planning for field operations with minimal impacts and environmental risks in view;
- Mapping and collection of exploration datasets without removing samples for analysis (including geological mapping, geophysical surveys, and any environmental or socio-economic baseline studies that can be undertaken at this stage);
- Collection of samples in the field for chemical analysis (including geological, mineralogical, and geochemical sampling);
- Invasive (explosive seismic) or non-invasive (hammer seismic, geoelectric, geomagnetic, geotelluric, etc.) geophysical surveys;
- Exploration drilling and sampling (via a variety of drilling techniques, incl. borehole geophysics);
- Drafting of the mineral and energy resource and reserve disclosure statement (in line with e.g. PERC (2021), UNECE (2021), and/or other applicable Codes and Standards) with respect to ESG requirements;
- Closure and remediation of the Exploration site(s).

Perhaps the most invasive operation during exploration is the drilling of boreholes. As boreholes for combined extraction are likely to be very deep, they will pass through various aquifers, which entails the risk of hydraulic short-circuiting and cross-contamination, if not carried out with the necessary care. Drilling sites also need to be made safe, so that any spilled drilling fluids, potentially contaminated waters, or drill-chippings can be contained and eventually removed for safe disposal, if needed. The preparation of the drilling-site itself may impact the local flora and fauna and the soil properties. Drilling operations are often noisy and may disturb local fauna as well as people nearby. The construction of access roads and the use of public roads for the transportation of materials and equipment will have further impacts to consider.

Similar considerations apply to reservoir seismic exploration, where also disturbance by blasting or vibro-seismic vehicles may be an issue.

Particular care must be exercised in vulnerable and low-metabolism regions, such as the arctic, alpine, or semi-arid regions, where self-healing of damages to ecosystems will take a very long time. Exploration may only be permitted during the cold season and when the snow-cover helps to reduce impacts. In some cases the whole operation is air-lifted into place to avoid surface disturbances.

Exploration results will feed into an assessment of resources and reserves compliant with CRIRSCO-aligned standards, PERC for Europe, and/or UNFC (for strategic resources management at national or EU level. As will be discussed in more detail in Chapter 5 and 6, this kind of resource classification will also consider potential environmental and societal impacts as well as the governance context of any future exploitation project in form of so-called modifying factors. This means in practice, that the respective potential life-cycle risks for an extractive project should be outlined at this moment.

It is important to remember that the area over which geophysical investigations have to be carried and over which boreholes have to be drilled will be much larger than the operational foot-print of the mines.

4.1.2 Project development

While the project development activities *per se* are not likely to entail any environmental or OHS impacts, their outcomes may well do. Planning for the whole life-cycle of the envisaged extractive operation is important in order to reduce its potential impacts in the ESG space. Such planning will encompass in the present the construction of the various shafts and adits, the siting and construction of the industrial facilities, namely the power-plant and the plant for the extraction of the metal value including storage area for reactants and products, management options for extractive and processing wastes, transport routes for reactants and products, etc. It is, however, understood that planning can only be based initially on the information collected from exploration and will need to be continuously updated as the construction of the mine and the actual extraction progress. This may also require an adaptation of the extractive waste management plans (cf. EWD, 2006).

The drilling of the various wells during exploration will give rise to a small amount of extractive waste, which will need to be managed according to the requirements of the Extractive Waste Directive (EWD, 2006). Any inert components of these wastes probably can be re-used on site for construction purposes.

Project development will include the permitting application procedures, as these will be iterative with more detailed planning. At this moment also the final EIA will be developed together with the mitigation plans for any risks and impacts potentially arising.

OHS risks during plant construction are akin to those of other drilling operations and construction sites and the respective safety at the workplace regulations will apply (cf. Chapter 3, namely the Directives 89/391/EEC (CEU, 1989) and 92/91/EEC (CEU, 1992)).

Interactions with (local) stakeholders will continue from the exploration phase, as stakeholder concerns may influence the design and mode of operation of the extractive operation.

One aspect during construction that may attract particular attention by the public are measures to increase the permeability, water/heat flows, and reactive surfaces down-hole. Such measures consist of pumping fluids at high pressure into the boreholes with a view to open up fractures and other discontinuities. The fractures etc. are kept open by pumping sand or zirconium spheres into the voids thus created. This technique is/was regularly used by the hydrocarbon industry to increase yield. Public concerns arose due to the use of flow-improving surfactants and the seismic activity caused or triggered. While in combined extraction facilities the use of reactants down-hole is generally not envisaged, there is the risk of seismic events due to the disturbance of the rock-stresses at depth by the extraction of waters or the ‘fracking’ process. Modelling of rock-stress changes will need to be foreseen in predict and control seismic activity.

While combined extraction projects are likely to have a rather long life-time, it is still necessary to make preliminary plans for closure, decommissioning, and long-term management of any extractive waste facilities constructed in particular.

Ideally, the combined extraction plant should also be integrated into the socio-economic fabric of the region.

4.1.3 Extractive operation and Processing

Unlike for most other extractive operations, the risks and actual impacts from combined extraction operations are relatively small. Once the plant has been built, there will be little changes to the surface features of the operation. All processes take place in closed circuits and inside buildings with virtually no emissions and releases under normal operating conditions. As has been discussed in Chapter 2, there is no clear distinction between extraction and processing compared to conventional mining, although there may be distinct sections in the plant (cf. Figure 2). Therefore, the risks discussed separately in the *Guidelines* (Eco-efficiency et al., 2023) are discussed here together.

The main operating risks would be spills and aqueous releases due to pipe breakages. Safety measures would typically encompass the construction of impervious basins around the plant to prevent releases into surface waters or sewers, as well as overflow tanks and similar. Whether the forthcoming Industrial Emissions Directive of the European Commission will apply to such installations remains to be seen.

From the OHS perspective, the main operating risks are the accidental exposure to hot and/or acid/caustic fluids, reagent chemicals, and the exposure to steam due to mis-operation or malfunctioning of equipment. Such risks are covered by Directives 89/391/EEC (CEU, 1989) and the subsidiary national workplace regulations. The chemical compounds used in the extraction processes may need to be assessed according to Regulation (EC) No 1907/2006 (CEU, 2006) for any specific workplace or environmental hazards.

It may be debatable, whether the wastes from extracting the metal value from the geothermal fluids are extractive or processing wastes, in other words under which legislation they should fall. Safe management routes will depend on the contents of certain elements or compounds, such as heavy metals, radionuclides, arsenic etc., for which no further use or recycling routes are foreseen. Some of these materials may be used on site for further construction purposes. Compared to other types of extractive operations these quantities will be very small. Organic wastes, such as spent ion exchange resins will need to be managed as industrial waste at licensed disposal or incineration facilities, if they cannot be recycled.

4.1.4 Closure, decommissioning and after-care

Once the combined extraction facility has reached the end of its useful life, e.g. due to temperature draw-down, exhaustion of target minerals, or clogging of the open permeabilities, it will need to be closed in an orderly fashion. This may include a slow re-establishment of the original hydraulic regime, if the combined extraction operation resulted in any such change.

Upon closure, structures above and below ground need to be decommissioned so that they do not constitute any long-term risks and cause in impacts. Once the well-head installations have been removed, the wells need to be capped to prevent foreign items entering them and causing contamination. Depending on the well design, casings may need to be drawn and certain layers be sealed in order to prevent hydraulic short-circuiting and cross-contamination. Installations and structures above ground will need to be dismantled, if no further use for them is foreseen. Any contamination in the ground from spills etc. will need to be removed and the site remediated, if necessary. Unless there is contamination by heavy metals or radionuclides, it can be foreseen that most materials can be directed to recycling.

Any extractive waste facility constructed during the operation needs to be closed and made long-term stable, if not designed in this way already. Respective guidance can be found in MWEI-BREF (2018).

4.1.5 Risk catalogues

The risk catalogues in Annex I aim to provide decision-makers, public stakeholders and also operators a comprehensive overview over the risks that may be encountered during the various phases of the life-cycle of an extractive operation. While the lists of potential risks attempt to be fairly comprehensive, it does not mean that all these risks would be relevant for a given extraction operation at the same time. The catalogue does not cover operational health and safety risks to the operator unless these may have also consequences to the environment, e.g. from the sabotage to vehicles or infrastructure.

The list mainly serves as a means to create awareness of potential risks and as a checklist. A considerable number of the risks listed are not specific to extractive operations, but would be associated with the various life-cycle phases of any industrial operation, such as chemical processing plants for instance.

The risks are organised by life-cycle phase and environmental compartment or other type of receptor potentially affected. This way of organisation means, that certain types of risks, for instance air emissions, reappear in different categories. It would have been also possible to organise this list by type of risk and then list their possible causes. However, the chosen structure allows to attribute risks more clearly to root-causes in each life-cycle phase for which different control measures might be appropriate.

It should also be noted that open-cast mines and processing plants are listed among the risk categories. It is, however, very likely that one would avoid open-cast mining in a protected area due to its comparatively high impact potential.

Likewise, one would avoid operating processing plants in such areas, but one would need to undertake a comparative risk assessment between processing on site and transporting the ore to a processing plant away from the protected area. With the tendency in modern deep mines to move as much of the processing underground, such as sorting and comminution, the amounts of ore to be processed would be minimised. In this way the tonnage to be transported away from the protected area would be minimised.

Wet or thermal processing of ores and the associated extractive waste management facilities are the steps with the highest impact potential.

4.2 Types of extractive wastes generated and disposal options

4.2.1 Challenges in extractive waste management

The main challenges are long-term stable and safe extractive waste management facilities. Ideally and as has been discussed above, such facilities should not be located within protected areas or in locations where they could interact in a detrimental way, e.g. upstream from such areas. This could be achieved for the relatively smaller amounts of processing wastes due to advanced sorting etc. techniques as discussed above, but a certain quantity of inert waste rock may need to be disposed of near the mine.

The main paradigm in keeping waste rock disposal facilities stable over the long-term is a design and construction of covers that mimic the natural environment in depth profile, composition as well as topography. Respective good practices can be found in MWEI-BREF (2018). While mimicking the natural soil profile, the covers may also have man-made geomembranes and geotextiles as components to prevent the ingress of meteoric water (as the main driver for acid rock drainage formation) or the exhalation of radon. In order to minimise erosion, the surface topography of extractive waste facilities should reproduce that of the surrounding landscape. Airborne LIDAR and satellite-based RADAR scans provide a detailed topographical mapping of the natural landscape after which slope angles, frequency and shape of surface features etc. can be modelled (see European Commission et al. 2019 and references therein). It should be noted that the resulting shape of the facilities does not necessarily have the smallest footprint or is the most convenient from an operational point of view, but will be the one that requires the least care and maintenance after closure (see below).

4.2.2 Types of waste

The types and quantities of waste generated depend on the geology, the mining and the processing methods. According to the EWD (2006) one needs to distinguish between inert and reactive wastes. In addition, one needs to consider also, whether these wastes have the potential to generate in particular acid rock-drainage (ARD) and, in the first place, whether an economic or otherwise beneficial use can be found (cf. Figure 1). The disposal of reactive wastes requires a specially licensed facility. Due their possible interaction with the environment, it will be undesirable to construct such facilities in protected areas. Backfilling (see below) or off-site transport of such wastes would be preferred.

Mining wastes arise from sinking access shafts and excavating drifts, adits, and other openings to provide access to the target mineralisation. Depending on the type of rock and the mining method, it can be anything from sand-like materials to large lumps of rock. The mineralogy in the resulting extractive wastes will be that of all rock types that are encountered while sinking shafts and excavating drifts etc. It may also comprise below-grade ore, or other minerals that are not targeted, though according the 'total extraction' paradigms promoted already by the EWD (2006) and reinforced by the CRMA (2024), such materials should not be considered 'waste', but beneficial uses for them should be found. All the rocks encountered could contain reactive minerals and a triage according to Figure 1 is required to find the appropriate management route.

Stripped top-soil is not to be considered waste according to the EWD (2006), but needs to be managed in a way that maintains its functionality. This can include its long-term storage for later rehabilitation efforts or it may be sold off to be used in other locations. The latter implies that during rehabilitation work suitable top-soil needs to be brought in from outside.

Although strictly speaking being processing waste, tailings are typically discussed in the context of extractive waste management. In principle, their mineralogy will be the same as that of the excavated rocks, albeit with modifications caused by the processing, such as acid leaching. Depending on the processing much of or all of the reactive minerals may have been removed. However, the tailings will contain residues of the processing chemicals, such as acids. The main challenge is their small and uniform grain size and the high water-content that requires their management in dedicated 'tailings ponds' (cf. EWD, 2006). Tailings also have a high potentially reactive surface area.

4.2.3 Backfilling Options

Backfilling of wastes into excavated voids has the overall advantage of avoiding their hoisting to the surface with the associated energy expenditure. It also reduces the permanent footprint of a mining operation on the surface and thus mining legacies that may need to be managed in perpetuity.

Backfilling may also be required for structural or mining strategic reasons. It stabilises the mined-out areas and allows to mine adjacent areas of a mineralisation (room-and-pillar mining). In this case a binder will be needed, which may be pristine material (e.g. cement) or may be in itself a waste product (e.g. hydraulic fly-ash). The use of additional materials will necessarily generate additional transport traffic across protected areas.

The processing of ores will have altered to some extent their mineralogical composition. Crushing and comminution greatly enhanced the potentially reactive surface area and exposes the surfaces of reactive minerals. The use of binders and solidifying agents can also have the purpose to reduce the accessible surface of the backfilled material.

The disaggregation due to excavation and/or processing necessarily leads to an increase in volume. The original density cannot be re-instituted, except for certain materials such as clays and other unconsolidated materials. The volume increase means that not sufficient space for backfilling of all excavated material will be available. Consequently, a certain amount of surface disposal area is required also in this option, unless the excess material can be directed to other beneficial uses outside of the mine (cf. Figure 1).

Another factor that leads to volume increase is, as noted above, that additional materials (e.g. cement, hydraulic fly-ash) are needed as binders to artificially stabilise materials destined for backfilling, particularly when the backfill is going to have structural functions. Binders can also serve to reduce porosities and thus the potential for minerals to become dissolved by percolating groundwaters after the closure a mine.

4.2.4 Surface disposal of extractive wastes

The construction of surface disposal facilities for extractives wastes in principle is undesirable in protected areas and should be avoided. This applies in particular to tailings management facilities, even when paste technology is used to reduce risks (GlobalTailingsReview, 2019). A (strategic) environmental impact assessment will have to evaluate the relative merits and impacts of disposal within the protected area against transporting the waste to a location outside this area. A full Life-Cycle Impact Assessment (LCIA) will need to look into the risks and impacts from transport, the potentially habitat disruptive impacts of transport routes (road, rail, conveyer-belt, cable-car, pipeline, water-way, etc.), including their construction and decommissioning (see Section 6.3 for a more detailed discussion). The Global Tailings Review Standard (GlobalTailingsReview, 2019) mandates to undertake a full contextual analysis in all dimensions, such as environmental, societal, etc.

If disposal within the protected area is considered, a location with the least impact and disruption needs to be found. This location should facilitate the integration of extractive waste facility into the existing landscape by adopting the respective slope grades and drainage patterns (see e.g. European Commission et al., 2019; Martin Duque et al., 2019), and in a way that ecosystem and habitat functions can be recreated.

The LCIA also needs to consider that the construction of an EWF as per MWEI-BREF (2018) and that mimics the surrounding landscape may result in an increased footprint, may entail the use of additional land to allow operations, and may require the import of alien materials for the construction of liners and covers, as well as top-soil if such could not be retained, when clearing the site.

4.3 Emerging sustainable mining technologies and practices

The assessment of best available techniques (BAT) across the extractive life-cycle reveals that technological advances are increasingly enabling mining with reduced surface footprint and environmental impact. As reviewed in CIRAN Deliverable D4.1 (Carriedo et al., 2024), emerging technologies, such as automated underground sorting, in-mine processing, and precision drilling techniques can significantly reduce both, the volume of material brought to the surface and the associated surface infrastructure requirements. These technologies, when combined with modern paste backfilling methods and advanced water management systems, provide operators with concrete options to minimise their impact on protected areas. However, the application of these techniques must be evaluated within the specific geological and environmental context of each site, as demonstrated in the comprehensive risk catalogues developed in this report.

The effectiveness of BAT in reducing environmental impacts varies significantly based on site-specific conditions. Deep mining operations employing advanced automation and underground processing have demonstrated the greatest potential for compatibility with surface protection objectives, while near-surface deposits remain challenging regardless of the technology employed. The review indicates that the most successful applications of BAT are those that address the entire life-cycle of the operation, from exploration through to closure and rehabilitation. This includes the integration of real-time monitoring systems, adaptive management approaches, and proactive rehabilitation strategies. These findings directly support the original objective of identifying techniques that could make extraction beneath protected areas environmentally viable, while also highlighting the limitations of technological solutions alone in resolving conflicts between resource extraction and environmental protection.

From the perspective of a low-impact low-visibility operation in a protected area, the optimisation along the life-cycle of the mine will be an important aspect. Every phase during the life-cycle should have as little impact as possible.

Figure 4 illustrates the life-cycle phases of a mine. Each step can be optimised with new technologies and the efficiency of the previous steps will set the scene for the following steps.

Exploration: Comprehensive and careful exploration helps to better locate the mineralisation, thus reducing the need for unnecessary extraction and extractive waste generation. Large amounts of geophysical (cf.

Section 2.5.8 in D4.1) and remote sensing data (cf. Section 2.3.11 in D4.1) will improve the knowledge of the mineralisation (cf. Section 2.3.8 in D4.1). The large amounts of data generated require modern data management techniques and with the aid of AI-supported modelling techniques (cf. Section 2.3.2 in D4.1) allow to more precisely predict the spatial extent of the mineralisation.

Exploration itself can have a wide variety of impacts and risks (see Section 4.1.1), beginning with the presence of mapping geologists in the area. Choosing an exploration strategy and technique that is compatible with and adapted to the protected area in question will be an important first step within the limits of efficacy. For instance, it may be preferable to use less invasive techniques, such as geoelectric or vibro-seismic techniques over classical seismic with explosives that require also drilling for deployment at depth. Drilling is likely to be unavoidable at some stage of exploration. In particular sensitive environments one will have to think of air-lifting the rig in place, as is already common practice in slowly regenerating environments, such as the Arctic tundra. In addition, the drilling pad has to be made self-contained (preventing the dispersal of contaminated materials or oils etc.) and all constructed infrastructure (e.g. concreted drilling-pad), equipment and drilling-wastes have to be removed. Depending on the situation, also deflected drilling from outside of the protected area may need to be considered (which is regularly practiced in the hydrocarbon industry). These measures are mindful of the fact that exploration can potentially impact a much larger area than the eventual mine site.

Project development: As has been pointed out *inter alia* in Eco-Efficiency et al. (2024), the planning stage in mine operation provides the key opportunity to prepare for a low-visibility and low-impact operations. Here strategic decisions are made with respect to mine layout and technologies as well as extractive waste management strategies and techniques to be employed. These in turn determine potential operational and long-term environmental and societal impacts.

A key planning objective for a mine within a protected area would be to keep as much of the operation and the associated extractive waste management underground, i.e. to minimise its operational and post-operational footprint. Some extractive waste on the surface will be unavoidable as has been discussed above: the mine will need a certain space underground to operate and when backfilling, the volume of waste will be greater than that of the original rock, as the original density cannot be attained again. A site for the disposal in accordance with the Extractive Waster Directive (EWD, 2006) and causing the least disturbance to the protected area has to be identified. While on-site or near-site disposal would be preferred from the perspective of transport-related impacts and costs, a disposal site outside the protected area may be preferable with a view to avoid permanent alterations to the protected area. A careful optimisation and balancing of advantages and disadvantages will be needed.

Planning should also aim to keep as much of the sorting, pre-processing and processing underground as possible, with a view to reduce the associated impacts and to keep the amount of material to be moved across the protected area as low as possible. Again, an optimisation model will be needed to decide which option has less impact while being feasible (technically, economically), processing underground or processing off-site (which involve transport beyond the boundaries of the protected area). Off-site transport will have associated impacts and risks (cf. Eco-Efficiency et al., 2024, and the risk tables in Appendix i), but these may be lower than those of on-site processing.

Mine ventilation is an important safety feature, but exhausts can cause disturbances due to the noise and the airflow. In some hard-rock mines discharges of radon can be a problem and have to be taken into consideration.

As the mines will be likely below the groundwater table, dewatering will be required, which may have important impacts on the local and regional water levels and hydrologic balances. Appropriate planning of the mine layout and sequence of extraction in 3D-space can help to minimise the volume to be dewatered and the amount of water to be discharged. Thus, waterproof liners in communication and other technical areas of the mine reduce water ingress and damming-up and backfilling worked-out mine areas reduce the volume to be dewatered and, hence, the overall water-table draw-down. While in most mines the drainage waters would be discharged into surface water-courses – after appropriate treatment for contaminants, this may be not an option for mine in a protected area in order to avoid changes in flow-rates and water composition. In this case a pipeline to a discharge point outside the protected area may need to be foreseen or discharge into boreholes some distance away from the mine. Such boreholes may not need to reach to the surface. A 3D-hydraulic model will help in the planning of water management. On the other hand, the treated mine waters could help to augment wet-lands or other surface-water features. In the latter case the ephemeral nature of the mining operation needs to be taken into account, meaning that such augmentation would cease, when mining ends.

Design for decommissioning and dismantling was perhaps first developed in the nuclear industry, but in the light of the recycling paradigm now has become a standard industry practice. The idea is to design components and plants so that their sequence of dismantling is facilitated and does not require additional construction or civil engineering works, which in turn helps to minimise the associated physical, energy, and carbon footprint.

Planning must also cover the eventual decommissioning wastes and management routes for them. On the other hand, there may be structures that could be used for the purposes of the protected area later, such as office buildings that could be used for park administrations, information centres, or similar purposes related to the management of the protected area. One could also think of converting head-frames into observation towers. Such further use can be already considered in the initial design phases, if the mining operation is expected to be of relatively short duration. This kind of re-use would reduce also the amounts of materials to be transported across the protected area during the decommissioning and rehabilitation phase.

Construction: The construction phase of a mine is possibly the one with the highest surface activities including transport of materials to the mine-site. Careful construction planning can minimise the additional footprint required during construction (and final closure and decommissioning).

The excavation techniques chosen will have significant influence on the amount of material removed and in the initial phase on possible disturbances due to generation of shock waves from blasting or generation of dust.

During the planning stage, a most effective and efficient mine layout, based on the available exploration data will have been developed. As construction of the access shafts and tunnels to the actual mineralisation progresses, this layout will be updated and refined on the basis of actual data on the geology.

Mine construction will also give rise to extractive waste that will have to be managed according to the Extractive Waste Directive (EWD, 2006). As mentioned before, these initial amounts of EW will be to be disposed of or stored on site, as there will not be sufficient volume underground for backfilling yet. Some of these wastes could be eventually used as backfill underground during the final decommissioning phase, a use that has to be foreseen explicitly in the extractive waste management plan (cf. European Commission et al., 2019) in order to be in compliance with the EWD (2006).

Operation: The operational phase is the one in which the target mineral(s) are being excavated. The choices of mining and processing technique determine, apart from the geological and mineralogical boundary conditions operational impacts and how much and what kind of extractive wastes are generated. The aim is to reduce unwanted extraction with a view to minimise waste generation and also to save energy and eventually footprint for the disposal of such wastes. In-mine and at-the-face exploration and assessment techniques help to refine the geological and ore body model built during exploration and thus to direct mine-development. Modern data management technologies (managing 'big data') are indispensable to keep track of the multiple data sources and the large amount of data arising from in-mine sensor technologies. Effectively, a 'digital twin' of the mine aids the data interpretation and mine-planning in quasi real time.

Advanced ore-sorting techniques down in the mine help to direct the material streams (waste rock, below-grade and commercial grade ore, etc.) and minimises the amount of material to be hoisted to the surface.

Mining down at the face is still one of the most dangerous jobs in the world and operators increasingly opt for automated and robotic solutions that are controlled remotely either from other areas in the mine or from the surface. Problems, such as the communication and geolocation of machinery in the mine are gradually being overcome through R&D projects sponsored mainly by the industry itself, but also through EU funding mechanisms. Collision monitoring systems create 'self-awareness' of autonomous machines to avoid incidents of machine-person and machine-machine collision.

Traditional drill-and-blast mining is improved with more efficient drilling technologies and explosives that leave fewer contaminating residues. As an alternative for softer rocks, excavation machines analogues to tunnel-boring machines are being developed and optimised. These result in less stress on the rock than blasting and continuous production lines from the face to sorting and comminution can be installed. Electrically powered, unmanned mining machinery allows to reduce the cross-sections of drifts, adits etc. thus allowing more targeted extraction and also doing away with the need for ventilation shafts, thus again reducing the amount of unwanted extraction.

Processing: A major concern are the aggressive chemicals in certain processes and the associated environmental risks. Improved pre-treatment for the comminution helps to increase the reactive surface area, in turn helping to reduce the amount of chemicals needed. As less-rich ores are expected to be encountered, also less intensive processing methods with less chemicals are under consideration, including bioleaching methods. These can be performed down-mine (e.g. H2020 project BioMOre, 2018), but also as ‘phytomining’ or ‘agromining’ on heap-leach pads.

While wet chemical processing is preferred in general over pyro-processing, electric arc-furnaces and hydrogen as energy carriers help to reduce the use of fossil fuels and thus carbon emissions, though SO_2 emissions from sulfidic ores remain to be controlled.

In situ leaching (ISL) can viewed as a combination of extraction and processing or as down-mine processing. It has the advantage of requiring comparatively little surface installations, but is only applicable to certain types of ores. The breadth of application could be widened with bioleaching methods (e.g. BioMOre, 2018). With the aid of directional drilling technologies, the surface installations for very deep ISL have the potential to be set up outside a protected area. Currently ISL is mainly used for uranium and copper ores, but research is ongoing to broaden the applicability. It needs to be supported by detailed hydraulic investigation and modelling in order to ensure that the system can be contained hydraulically.

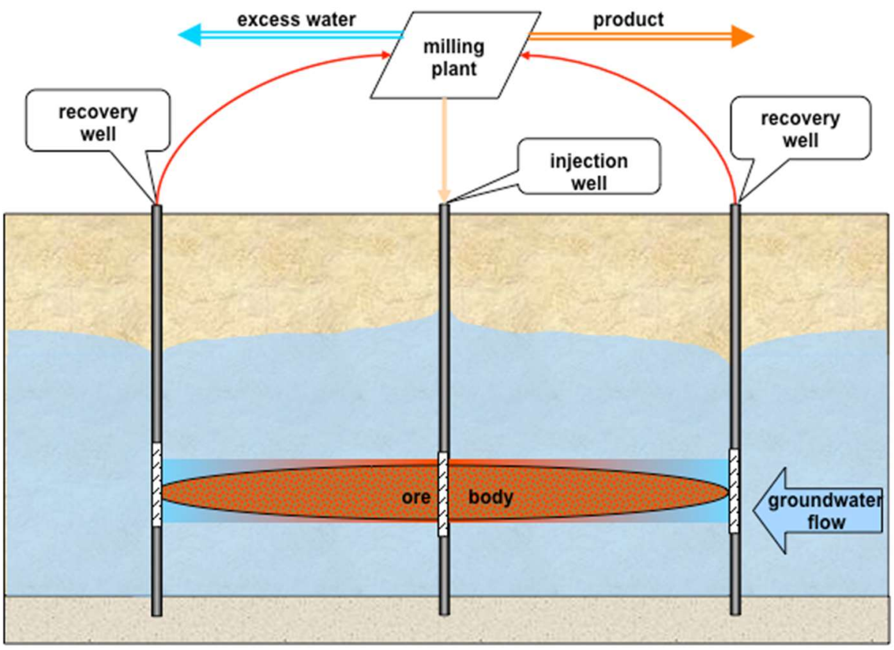

Figure 6: The principle of in situ leaching (ISL).

Closure, rehabilitation, and after-care: For many years it has already been recognised that a key concept for low-impact mining is to have in place right from the beginning a life-cycle management plan that encompasses also the post-mining period (e.g. Falck, 2016). This is acknowledged in the Extractive Waste Directive (EWD, 2006) and most EU jurisdictions require bonds or similar instruments to provide funds for an adequate closure and rehabilitation of mining sites even in the event that the mine has to close prematurely due to economic conditions or the mining company fails.

Progressive rehabilitation, as operations permit and as advocated by the EWD (2006), helps to reduce the effective footprint of a mine on the surface and the active areas down in a mine during its operational phase. This may involve regrading slopes and constructing covers as discussed above. Apart from the topography that can be monitored for erosion losses by various remote sensing technologies, sustained revegetation is important for the long-term stability of extractive waste facilities, which also can be monitored *inter alia* with drone-borne or satellite-based remote sensing. Remotely controlled ground-based monitoring, such as electrical resistivity tomography, will provide early warning signals, when key system components, such as tailings dams begin to be compromised.

Actual soil remediation should not be necessary at a properly managed mine site, but accidents cannot be prevented with 100% certainty. Over the last few decades, a wide variety of rehabilitation strategies and techniques with varying degrees of invasiveness have been developed. It is always important to strike a balance between the impacts of the actual contamination and any collateral impacts that may arise from the deployment of rehabilitation technologies. Thus, some soil rehabilitation techniques will remove the contaminants, but also result in fertility loss due to the humus and microbial content being destroyed by process chemicals.

Contaminated mine and rock drainage and the resulting impact on aquatic systems is a major challenge during the post-operational phase of many mines. Ideally, the problem is being treated at its root, no reactive materials are deposited on the surface and open underground mine workings are dammed up and/or backfilled. Also, comprehensive extraction may strip ores of such minerals that can give rise to acid drainage. With the deep mines envisaged for extraction beneath protected areas and with the strategy to reduce unwanted extraction as much as possible and to leave as much as operationally possible the material below ground, the problem can be at least partially addressed at its root.

Overall sustainability aspects: In line with the general socio-technological trends to move away from fossil fuels as energy sources through the electrification of all aspects of mine operation with energy being harvested from wind, solar radiation or nuclear fission, helps to reduce the carbon footprint of mine-operations. Hydrogen as energy carrier may be an option in surface mines, but will pose safety-challenges in deep mines, where battery-operated vehicles (mainly rail-bound) have a long tradition. Carbon capture and storage (CCS) has been already implemented in various mining operations, but should be viewed only as transitory solutions, as it does not remove the root-cause of carbon emissions. Energy is one of the main operational expenditures in mining and, therefore, the industry actively pursues strategies to make operations more energy and thus also more cost efficient by improved mining and milling techniques and less material being excavated and hoisted to the surface.

5 Assessing the extractability and economic viability of deposits

5.1 Frameworks for assessment

5.1.1 Overview

A variety of stakeholders have a vested interest in accurate data on the occurrence and availability of mineral resources. Governments need such information for strategic decision- and policy-making, for instance with respect to the mid- to long-term supply security. Investors, who fund extraction need to base their decisions on reliable data on the likely viability of projects. However, not only data on the physical presence of mineral resources are of importance, but also information on their extractability and any circumstances that may pose an obstacle to their extraction. In addition, the dimension of time plays a role, as in the early phases of a potential project the level of knowledge of the mineral occurrence is low and exploration activities aim to decrease the level of uncertainty for the data users and, hence, increase the level of knowledge and confidence. It is therefore essential that the industry communicates the risks associated with investment effectively and transparently in order to earn the level of trust by capital allocators necessary to underpin its activities.

It is clear, that the information needs of governments and industry/investors are somewhat different. On the other hand, as mineral resources extraction and use are a global business, an alignment of the way how resources are assessed and reported was desirable, both from a business as well as a strategic planning perspective.

5.1.2 Industry resource reporting – CRIRSCO aligned codes

The Committee for Mineral Reserves International Reporting Standards (CRIRSCO, https://crirsco.com/), which was formed in 1994 under the auspices of the then Council of Mining and Metallurgical Institutes (CMMI), is a grouping of representatives of organisations that are responsible for developing mineral reporting codes and guidelines in Australasia (JORC), Brazil (CBRR), Canada (CIM), Chile (National Committee), Colombia (CCRR), Europe (PERC), India (NACRI), Indonesia (KOMBERS _ KCMI), Kazakhstan (KAZRC), Mongolia (MPIGM), Russia (NAEN), South Africa (SAMREC), Turkey (UMREK) and the USA (SME). The combined value of mining companies listed on the stock exchanges of these countries accounts for more than 80% of the listed capital of the mining industry.

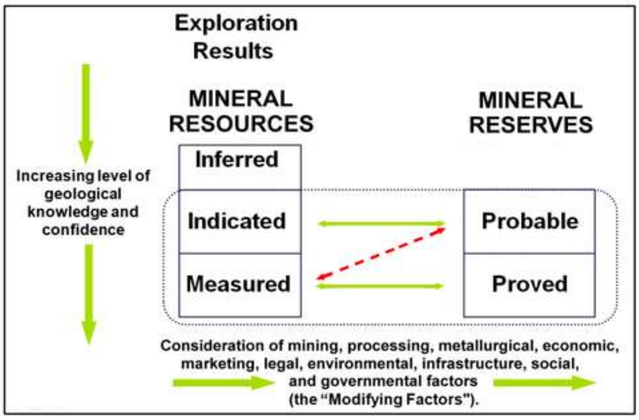

Figure 7: Mineral resources and reserves according to CRIRSCO definitions.

The international initiative to standardise market-related reporting definitions for mineral resources and mineral reserves had its start at the 15th CMMI Congress at Sun City, South Africa in 1994. The mineral definitions working group (later called CRIRSCO) was formed after a meeting at that Congress with the primary objective of developing a set of international standard definitions for the reporting of mineral resources and mineral reserves. Figure 7 illustrates the classification of mineral resources and reserves according the increasing level of confidence as exploration and exploitation progresses.

The similarity of the various national reporting codes and guidelines has enabled CRIRSCO to develop an International Minerals Reporting Code Template (CRIRSCO, 2019). This can act as a "core code and guidelines" for any country wishing to adopt its own CRIRSCO-style reporting standard, after including provisions for country-specific requirements such as those of a legal and investment regulatory nature. Following discussions over a number of years, CRIRSCO published Standard Definitions in October 2012. These fifteen definitions have been incorporated in International Reporting Template of CRIRSCO dated November 2013 and in the Codes and Standards of most of the CRIRSCO Members in their own updates.

Accordingly, The Pan European Reserves and Resources Reporting Committee (PERC, https://percstandard.org/) developed for Europe a Standard for Reporting of Exploration Results, Mineral Resources and Mineral Reserves (https://percstandard.org/wp-content/uploads/2021/09/PERC_REPORTING_STANDARD_2021_RELEASE_01Oct21_full.pdf), which sets out the minimum standards, additional guidelines and recommendations for the Public Reporting of Exploration Results (including Exploration Targets), Mineral Resources and Mineral Reserves.

A key aspect that determines, whether a mineral occurrence can become a viable extraction project are the so-called 'Modifying Factors' (cf. https://crirsco.com/docs/CRIRSCO_standard_definitions_oct2012.pdf) that include, but are not restricted to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, societal and governmental factors. In other words, they are concerned with the questions that are vital for a deciding whether permitting extraction in a protected area is justified or not.

5.1.3 United Nations Framework Classification for Resources (UNFC)

The United Nations Resource Management System (UNRMS; UNECE, 2019) provides countries, companies, financial institutions and other stakeholders a tool for sustainable development of energy and mineral resource endowments with the framework of the UN Sustainable Development Goals (https://sdgs.un.org/2030agenda). The UNRMS applies to energy resources including oil and gas, renewable energy, nuclear energy, minerals, injection projects for the geological storage of CO_2, groundwater, and anthropogenic resources, such as secondary resources recycled from residues and wastes.

Thus, the UNRMS is designed to be a:

- Global voluntary system for resource management to be used by governments, industry, investors, and civil society;
- Innovative integrated resource management framework for resources such as minerals, petroleum, renewable energy sources, nuclear resources, anthropogenic resources, geological storage and groundwater to support the development of policies and regulations in the sustainable management and advancement of the Sustainable Development Goals (SDGs);
- Comprehensive information framework and methodology to support resource progression applicable for programme, portfolio, project and asset-level management;
- Sustainability framework to aid the financing of resource sectors;
- System for local and indigenous communities for evaluating and assessing projects against stated environmental-social-economic objectives;
- Scheme for long-term considerations of commercial and policy aspects of projects;
- Design of conditions for the industry to harness the integrative dynamic capabilities;
- Support kit for projects to help align with applicable regulations;
- Instrument to support sustainability and financial reporting.

The emerging challenges in these sectors are the sustainable, environmental-friendly, carbon neutral and efficient development, harvesting of energy and raw materials required for a growing population. Innovations in production, consumption and transportation are fundamentally challenging how energy and material sectors function today. As a unique tool for harmonising policy framework, government oversight, industry business process and efficient capital allocation, UNFC is designed for managing the natural resources required for the present and future needs of society and realising the objectives of the United Nations Sustainable Development Goals (SDGs, https://unece.org/sustainable-energyunfc-and-sustainable-resource-management/unfc-and-sustainable-development-goals).

The United Nations Framework Classification for Resources (UNFC, https://unece.org/sustainable-energy/sustainable-resource-management/united-nations-framework-classification). in its core principles, encompasses a tool for the comprehensive management of all socio-economical, technological and uncertainty aspects of energy and mineral projects. The project maturity and resource progression model of UNFC can de-risk projects from costly failures and thus protect the investments, but also the environment from unnecessary and unviable projects. UNFC fully integrates social and environmental considerations and technology-readiness required.

UNFC aims to provide clear and consistent specifications, guidelines and best practices for all energy and mineral sectors.

To help the application of UNFC uniformly worldwide, guidelines on requirements for competency of the personnel are included in the system. UNFC provides case studies and implementation examples, not only to improve the consistencies in the usage but also to enhance the system through innovative applications.

Sustainable management of energy and raw material resources in a rapidly changing global economic landscape requires accurate mapping of supply and demand. The recoverable resources available on our planet need coherent and consistent definition and categorisation at global, regional, national and local levels.

UNFC is a principles-based system in which a resource project is classified on the basis of the three fundamental criteria (UNECE, 2021) of

- Environmental, socio-economic, and regulatory viability (E),
- technical feasibility (F), and
- degree of confidence in the estimate (G),

using a numerical coding system. Combinations of these criteria create a three-dimensional system (Figure 5). Categories (e.g. E1, E2, E3) and, in some cases, Sub-categories (e.g. E1.1) are defined for each of the three criteria.

The first set of Categories (the E Axis) designates the degree of favourability of environmental-socio-economic and governance (ESG) conditions in establishing the viability of the project, including consideration of market prices and relevant legal, regulatory, societal, environmental, and contractual conditions.

The second set (the F Axis) designates the maturity of technology, studies, and commitments necessary to implement the project. These projects range from early conceptual studies through to a fully developed project that is producing and reflects standard value-chain management principles.

The third set of categories (the G Axis) designates the degree of confidence in the estimate of the quantities of products from the project.

The Categories and Sub-categories are the building blocks of the system and are combined in the form of 'Classes'. UNFC can be visualised in three dimensions, as shown in Figure 8 below.

For more details, the reader should consult the Supplementary Specifications for the Application of the United Nations Framework Classification for Resources to Minerals (UNECE, 2021).

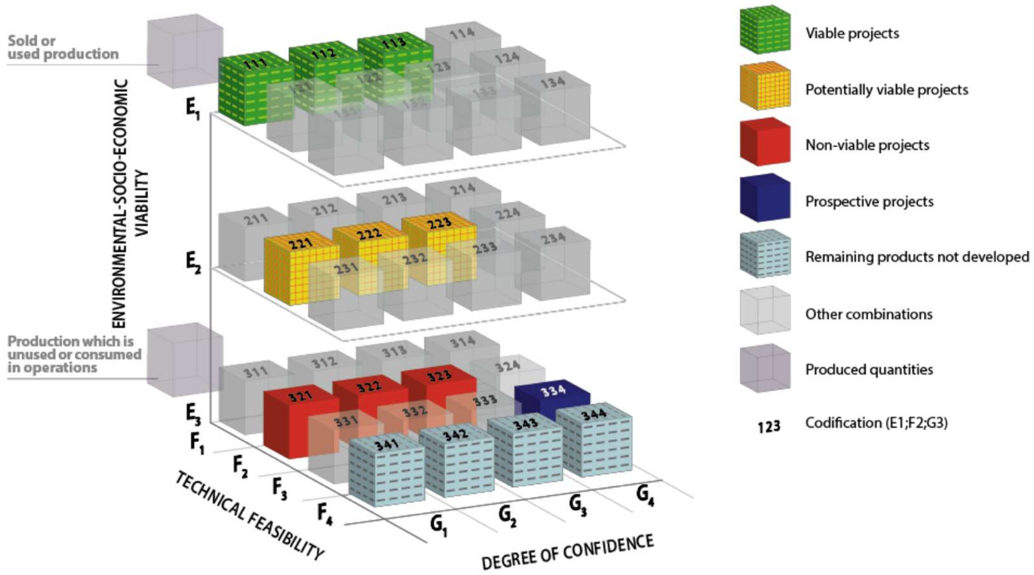

Figure 8: UNFC Categories and example of Classes.

Also of interest are the guidelines for the extraction of uranium (UNECE, 2017), in particular the section on extraction by *in situ*-leaching (ISL). ISL could be envisaged as method of recovery of metal value, integrating both, excavation and processing, into a single step.

It needs to be kept in mind, that the UNFC in the first instance was developed to assess (and manage) resources at a country level with a view to make policy- or strategic decisions and not to manage particular projects with respect to financial decisions. However, in recent years the difference between CRIRSCO-aligned reporting and classifications according to UNFC has become somewhat blurred. To help understand the differences, a so-called 'bridging document' (UNECE, 2015) was developed early on (cf. Figure 9) and was recently revised (UNECE, 2024). Unlike the CRIRSCO-template, UNFC also allows to classify also currently non-viable projects, whereby the viability may be impaired along any of the three axes, and to make estimates about the likelihood of becoming viable in the future. Thus, a mineral occurrence underneath a protected area can be classified under UNFC (E3.2), but would remain a non-viable project until the permitting has been resolved. If strict protection will not permit mining, the occurrence may be classified as E3.3.

CRIRSCO Template		**UNFC-2009 "minimum" Categories**			**UNFC-2009 Class**
Mineral Reserve	Proved	E1	F1	G1	Commercial Projects
	Probable			G2	
Mineral Resource	Measured	E2	F2	G1	Potentially Commercial Projects
	Indicated			G2	
	Inferred			G3	
Exploration Results		E3	F3	G4	Exploration Projects

Figure 9: Simplified Mapping of CRIRSCO Template to UNFC-2009 Classes and Categories (UNECE, 2019).

The revised version of the Bridging Document (UENCE, 2024) explains the purposes of both, the CRIRSCO Template and the UNFC: "The CRIRSCO Template aligned reporting codes and standards focus on the detailed requirements for market-listed mineral companies to substantiate the conclusions of their activities transparently regarding the reporting of volumes of mineralised material on a mineral asset(s) owned by a minerals company, with the prime objective of supporting exchange regulation and avoiding market abuse.

UNFC provides a logical framework for the comparison of the estimated mineral products that may be derived from an entire mineral project in terms of aggregated estimate quantities, the maturity and feasibility, the degree of technical environmental-socio-economic viability and the level of confidence in those assessments."

The European Commission has been advocating the use of UNFC in resource-related projects inter alia to make classifications compatible with the EU Raw Materials Information System (RMIS, https://rmis.jrc.ec.europa.eu) developed by the Commission's Joint Research Centre (JRC). UNFC provides a high-level overview of potential opportunities, while CRIRSCO-aligned reporting provides a selective perspective of mineral endowments as only 'viable' projects are effectively reported. UNFC is well tailored for resource inventories, since it encompasses all ('viable' and 'unviable') deposits / projects.

5.2 Processability

The mineralogy of the target mineralisation determines, how it can be processed, i.e. what kind of processing technologies can be used. Again, this can only be assessed once samples are available.

As the processability can only be verified once larger quantities of the target mineralisation become available, the final decision on the exact type and layout of the processing plan can only be made with certainty at a relatively late stage of project development. Nevertheless, certain principal routes become likely apparent at a relatively early stage. Thus, it will be known, what kind of beneficiation, comminution and concentration may be needed, and whether hydrometallurgical or pyrometallurgical processes would be optimal.

The choice of extraction process, depends on the availability of ancillary process materials and reactants, the likely environmental impacts and their controllability, as well as the resulting wastes and their disposal requirements, but also on regulatory preferences. Today in general hydrometallurgical processing is favoured over pyrometallurgical processing due to the potentially lower environmental impacts.

It will also need to be investigated whether and which process steps may be carried out underground with the view to reduce the amounts of extractive waste needing disposal above ground. Likewise, processes need to optimised with a view to reduce the volume of tailings requiring disposal.

These technical investigations would go in hand with economic assessments in order to ensure the commercial viability of the chosen processes.

5.3 Economic viability of deposits vs. supply security criteria

While the economic viability of a deposit will be determined in the first instance by the market price of the respective commodity and the overall cost of extraction, concern over the supply security for certain mineral raw materials add another layer of criteria. It is beyond the scope of CIRAN to review in full possible or desirable socio-economic development trajectories and their ensuing mineral raw materials needs. Basis for the assessment is the criticality assessment now enshrined in the EU Critical Raw Materials Act (CRMA, 2014). The Act distinguishes between Strategic and Critical materials and provides algorithms for calculating the relative importance on the basis of criteria, such as the geographical spread of resources, the potential for exposure to supply disruptions and others. In these assessments, changes to the demand side, e.g. due to technology evolution, are considered only to a limited degree. This situation leads to decision-making processes with a great degree of uncertainty with respect to the boundary conditions.

When taking the decision to extract from underneath a protected area, one needs to be aware that there will be delay of several years, mainly due to the construction time for the mine, between the decision and the first mine product reaching the market. This will add another layer of uncertainty to the decision-making process, as the market conditions will have changed from the time the decision was made. Using the DPSIR-model will help to better understand some of the underlying uncertainties, as will technology foresight studies.

6 Integrating natural values, mining processes, and geological settings

6.1 Strategies to reduce impacts on protected areas

In the following the mid-to-long-term environmental and societal impacts of extractive activities in environmentally protected areas will be assessed. Real cases of extraction in or near protected areas have been collated as part of WP2 (Luodes et al., 2024). These cases will be reviewed with respect to performance gaps with a view to comparing what was expected from technologies, processes and strategies at the design/permitting stage and what communities and ecosystems experienced at the implementation stage.

As becomes clear from studying the risk catalogues (see Annex), different aspects of mining have different impacts on different environmental compartments. Therefore, different strategies can be applied to reduce or avoid the respective impacts. One strategy can be to move the source of the impact to outside of the protected area (cf. Figure 4).

Different functional elements of a mine can give rise to different types of impacts. Some of these impacts can and will occur at the surface, while other occur at depth and may not concern the surface. It may be helpful to distinguish between the mine zone underground, the industrial installations above ground, and any extractive waste management facilities on the surface. A deep mine may not have any functional relationship with ecosystems at the surface apart from the effect of dewatering the mine (groundwater table draw-down). In many parts of Europe, mines targeting CRMs are likely to target deeper occurrences as many near-surface occurrences may have already been mined out (although perhaps targeting other minerals). Industrial installations at the surface can be designed to minimise impacts (minimising footprint, enclosed operations to minimise dust and noise generation, etc.). The elements with the most significant and lasting impacts will be the extractive waste management facilities. Their footprint is determined by the volume of the excavated materials and the geotechnical requirements for slope stability. Tailings-ponds require substantial retaining structures (dams).

6.2 Moving the source of impact

While ideally the surface installations of a mine would be placed vertically above the main mineralisation with a view to minimise the amount of unwanted extraction, there are other factors to consider. These could be geotechnical, but could be also related to the land availability for the surface installations and extractive waste disposal, and, indeed, land use conflicts between mining and protected areas. In mountainous terrain also horizontal access tunnels are common. Tunnels have the advantage of potentially allowing higher transport volumes than systems with head-frames and vertical shafts. The cages in the shafts limit the size of pieces of machinery that can be brought into the mine, while a tunnel may allow to move almost complete machines to the face. Various mines around the world use inclined access tunnels. Although the volume to be excavated would be larger than for shafts, inclined tunnels could offer one way to access a deposit from the outside of a protected, without leaving a footprint in that area. As various interconnected (former) coal mines e.g. in Germany and the UK (e.g. https://www.northyorkmoors.org.uk/planning/sirius-minerals-polyhalite-mine-woodsmith-mine) have shown and as it currently practised e.g. in Boliden's Kristineberg-Renström mine in Sweden, it is also possible to access a deposit through a shaft that may be kilometres away from the deposit. The cost of excavation, the space available for the disposal (or storage) of the waste rock must be balanced against the impacts caused in the protected area otherwise and the economic feasibility.

6.3 Transport logistics vs. habitat fragmentation

All life-cycle stages of a mine generate a considerable amount of traffic in and around the site. Equipment and materials have to be brought to the site and products and perhaps also wastes have to be removed from the site. The related infrastructure and persistent and frequent road or rail movements can lead to habitat fragmentation. Habitat fragmentation can have significant impacts on ecosystems and biodiversity, although the loss of area may be small, and should be reduced (Dudley, 2008).

There are mining techniques and strategies that have the potential to reduce this traffic, but they may have other disadvantages and a careful cost-benefit analysis is required across the whole life-cycle and all aspects in order to quantitatively balance benefits and detriments. A life-cycle impact analysis for each mode of transport under consideration should be carried out.

When mining a protected area, other criteria than monetary costs will have a significant bearing on the final decision. Thus, one may choose a mode of transport with less impact even though the cost may be higher.

Depending on the volumes to be transported and expected duration of the operation the baseline options are road- or rail-transport under normal circumstances. Road transport is more flexible and may incur lower capital expenditure (CAPEX), as building a road typically is cheaper than building a railway line. This contrasts with the higher maintenance cost of rail infrastructure. In certain types of exploitation of natural resources, e.g. forestry or large-scale plantations, narrow-gauge industrial railways are still common and are cost-effective. Unlike standard-gauge railways, which require a significant amount of preparatory civil engineering work, such railways can be constructed 'on the fly' on reasonably level ground and would be less disruptive to the environment.

Other options would be industrial overhead cable-cars or conveyor belts. The latter, while avoiding the emissions from IC combustion engines of road-transport, can be very disruptive due to the noise generated and they may be an unsurmountable barrier for wildlife, thus leading to eco-system fragmentation. Conveyor belts are only suitable for the transport of disaggregated materials. Cable-cars on pylons are more silent in operation and do not lead to fragmentation of ecosystems, but there is a higher risk of complete disruption due to technical failure compared to individual lorries. They can be used also to transporting materials, but are not normally designed and licensed for the transport of personnel.

Tailings, when still liquid can also be pumped through pipelines over considerable distances. However, pipelines above ground can fragment ecosystems and habitats and may not be operable under freezing conditions. The desirability of operating processing plants within protected areas could be questioned. A strategic environmental impact assessment will have to weigh the pros and cons of options.

Figure 10: Trolley system for heavy mine hauling trucks in Australia (Source: https://www.australianmining.com.au/mining-decarbonisation-innovations-charge-on/).

The construction of access roads will be unavoidable, but other transport modes in addition can help to reduce the impacts in protected areas from high transport frequencies. Such alternative or additional modes of transport can also reduce impacts from IC engines in protected areas by externalising these to other areas.

A similar effect does have the electrification of all vehicles operating in the mine and for transport from and to the mine. This is already a tendency in various mining operations. Such vehicles can be battery operated or through overhead catenas, similar to trolley-buses and several large mine-operators already employ such systems for their heavy hauling equipment (Figure 10).

6.4 Integrating societal expectations

As noted earlier, stakeholder value-driven views on mine design, extractive waste management options, and rehabilitation solutions can have a decisive influence on the implementability of a mine project, irrespective of the formal license given by regulatory authorities. This complex procedure is commonly referred to as achieving a Social License to Operate (SLO).

This subject of SLO treated in detail in CIRAN Workpackage 5 and a considerable amount of literature on the subject has been developed in more recent years with respect to technology selection (e.g. Erdmann et al., 2017; Falck et al., 2017; Endl et mult. al., 2019). Tost et al. (2021) developed recommendations for procedures to achieve SLO specifically in a European context, as much of the previous scientific literature was concerned with situations in other parts of the world, where relations to indigenous peoples dominate the narratives.

However, the interrelations between nature protection, fulfilling the needs of the local and of the wider societies at regional, national and EU level, resource availability and global geo- and economic politics are much more complex. Figure 11 tries to capture some of these relations and interdependencies.

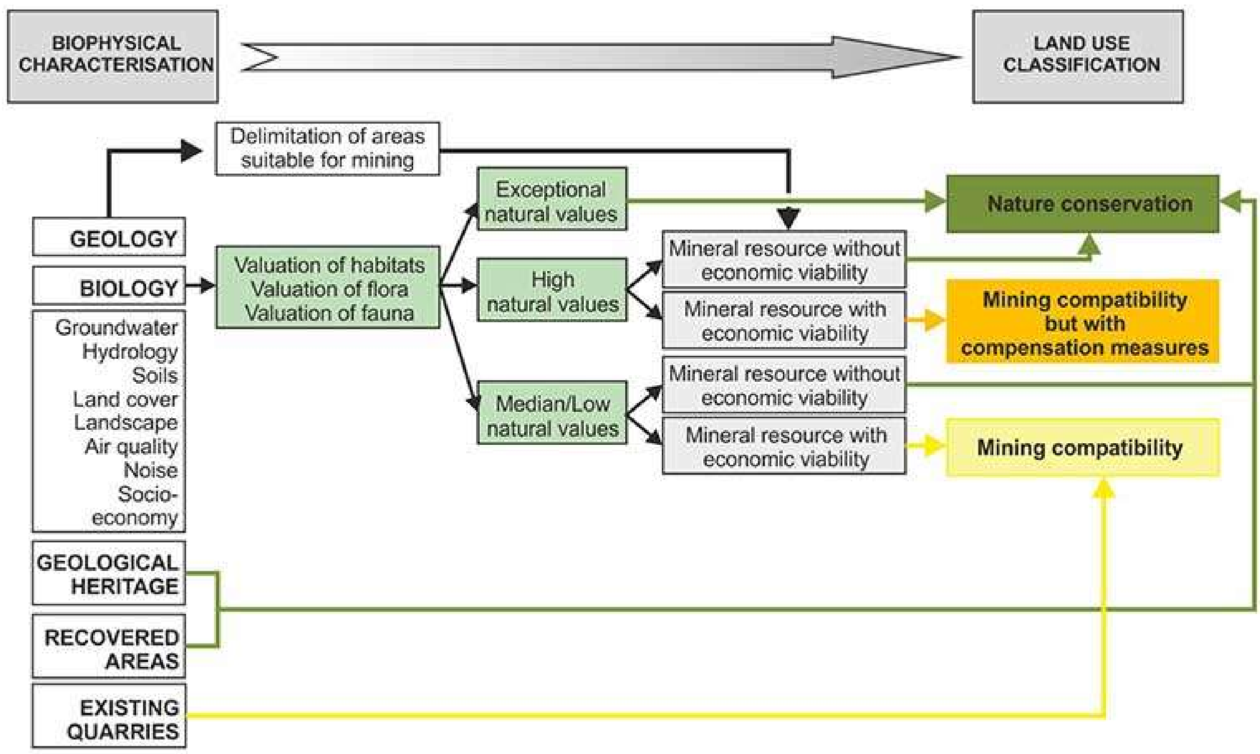

Figure 11: The complex relationship between exploitation of geological resources, societal expectations and nature protection (from Carvalho et al., 2016).

While the current report focuses on the more technical aspects of the processes that lead to the justification of permitting extraction from underneath protected areas, CIRAN Deliverable D6.2 (Hilton et al., forthcoming) will address the deeper societal dimension in a socio-political and policy-making context.

Integrating in particular the societal dimension in a more quantitative way into the assessment and then the decision-making processes (cf. Ch. 7) has always been a challenge and various strategies have been explored over time. For example, the GIASONE process (see below) developed by Leoni et al. (2024) in Italy offers the possibility with the aid of geographical information system (GIS) not only to integrate geological and geographical aspects, but also the socio-economic ones. It thus provides a multidisciplinary analysis tool that allows a dynamic approach to identify the intricate relationships of selected themes, modelling the territorial reality with the aim of proposing multiple scenarios to evaluate, distribute, and evenly mitigate the benefits and negative impacts on the entire territory. The “sustainability” index obtained by applying the GIASONE method utilises the following data categories, the initials of which form the acronym: G (geology, geography, hydraulics, hydrogeology...), I (mining industry data), SO (socio-demographic data), N (Nature, environment, agricultural and forestry resources), E (economic data). For each territorial segment derived from the comparison of indicators, a “sustainability” index – the GIASONE index - is calculated by summing the indices related to each indicator, multiplied by the weights associated with their respective categories.

6.5 Long-term environmental management

Much of the previous discussions have not explicitly considered the dimension of time. Any mining operation will leave behind some legacies in form of cavities (in the case of near-surface extraction) or of extractive waste management facilities (spoil heaps, tailings ponds, etc.) that have to be managed in perpetuity.

Risks and potential impacts from mining operations arise over different time-scales. Mine operators tend to focus on short-term and operational risks, while on the other hand many impacts can and will arise only after the end of the actual operation.

Risks and impacts will be considered in the long-term, from the construction of extractive facilities/ infrastructure to closure, rehabilitations and possible constraints on the rehabilitation and after-use of such sites. In addition, in a systemic and comprehensive environmental assessment, other impacts and risks, such as health & safety risks to workers, communities, and natural ecosystems will need to be considered.

This evaluation will build inter alia on international experience, the principles of environmental impact assessments, the MWEI-BREF (2018) and the forthcoming DG ENV guidance on risk assessment in the extractive industries (Eco-Efficiency at al., 2023).

An extractive operation alters the properties, features and functions of an area above and below ground compared to the pre-extraction situation. Some of the alterations are permanent, while others are (partially) reversible. Closure, rehabilitation and post-closure includes all activities that aim to mitigate impacts and liabilities that have arisen due to the construction and operation of the mine. These activities are undertaken to ensure that land used for mining is left in a safe, stable and non-contaminating condition that comply with the status of a protected area. These activities need to be planned before, and implemented during the operational phase. As improved information is gathered, this is assimilated into the plan and ongoing activities (e.g. rehabilitation trials and concurrent rehabilitation) of the site. It is acknowledged that some activities can only be carried out at the end of operation (e.g. the covering of a heap), with final plans only being confirmed as and when appropriate given the status of the broader context (e.g. climate) of the site.

Closure - Long-term environmental and geotechnical safety is different from the operational safety in the sense that the latter is built on the assumption that systems are constantly monitored and maintained, and the safety and health of mine employees is the main concern. The occupational safety and health systems allow extraction sites to operate in conditions that may not be naturally stable, such as slope angles, open pit walls, and mine-dewatering. On cessation of mining operations, the occupational safety and health focus (once all decommissioning activities are completed) shifts to ensuring the health and safety of the public and future land users and downstream receptors from the extractive site. Closure has to result in a return to naturally stable conditions under which no off-site contamination occurs and remaining site features do not pose any adverse effects on the environment or on human health. Closure has to arrive at a site end-state, where no significant residual risks of high impact and/or high probability remain.

Closure entails the removal of surface structures (decommissioning and dismantling), making underground voids and open pits safe against collapse, sealing of boreholes, shafts, adits etc. against groundwater short-circuiting and human intrusion or accident (cf. Hamor et al. 2021). The cessation of mine dewatering during closure has to proceed gradually in order to not cause collateral damage. Mine closure also involves the orderly closure of Extractive Waste Facilities (EWFs) according to the submitted Extractive Waste Management Plan (EWMP) as per minimum requirements established in the Extractive Waste Directive (EWD, 2006), following the practices laid down in the MWEI-BREF (2018).

As closure is also a mine life-cycle step with administrative and regulatory significance, its scope and implementation will vary from MS to MS. Guidance on process steps for closure has been summarised from an EU perspective in C&E (2021). In order to minimise life-cycle risks, closure plans should be developed at the mine planning stage and updated at suitable intervals or when major operational decisions are made.

Rehabilitation - Closure typically also requires the final rehabilitation of certain features and/or environmental compartments at the former extraction site. What is considered a closure activity and what is rehabilitation may vary from jurisdiction to jurisdiction. However, these activities aim to rebuild long-term stable conditions both above and below ground. Rehabilitation may include the removal or otherwise making safe of potential sources of contamination, the rebuilding of ecological functionalities that are appropriate to the agreed post-closure land use and the removal or reduction of contamination in certain environmental compartments, such as soils, surface- and groundwaters, if needed.

Where possible, rehabilitation activities are undertaken during the operational phase, thereby reducing the total burden on the post-mining phase.

Post-closure (long term) management - Whether a chosen technical solution for closure and rehabilitation will be stable over the long term depends in part on the post-closure use of the site. Post-closure management begins at the planning stage of a mine site. Local and regional (planning) authorities and public stakeholders are consulted in the development of closure plans to assist in the determination of a sustainable and beneficial post-extractive operation land use that is compatible with the status as a protected area. This provides, if necessary, a vehicle to ensure that site monitoring and maintenance continue to be carried out. It is important to recognise, that the solution needed for protected areas may go beyond what companies and/or regulators normally consider necessary from a purely technical perspective.

Long-term management is an emerging issue, and no explicit standards are yet available. The majority of the large body of guidance on mine closure and rehabilitation does not explicitly address the assessment and the management of long-term risks. When implementing technical solutions, it is usually tacitly assumed that they are maintained in order to keep residual risks at levels when first implemented (assumption of long-term stewardship).

The Extractive Waste Directive (EWD, 2006) requires the preparation for closure for extractive waste facilities, while the MWEI-BREF (2018) provide comprehensive guidance on the technical solutions for closure and rehabilitation. Many of the important mining countries have issued guidance on the closure and rehabilitation of extractive operations, e.g. MAC (n.d.), WB (n.d.) VCS (2020). Similarly, with the view to improve the sustainability of extractive operations and to reduce the legacies left to future generations, various international bodies developed guidance for mine closure. e.g. the APEC (2018), ICMM (2019, 2020).

The best documented cases of environmental rehabilitation with respect to their long-term stability and risks are arguably those of uranium mining. The International Atomic Energy Agency (IAEA) has published a comprehensive body of guidance on the long-term assessment and management including stewardship (IAEA, 2006 and references to earlier topical reports therein) and on monitoring (IAEA, 2002) since the mid-1990s. Although addressing nuclear installations (including processing plants), IAEA (2010) provides comprehensive guidance on seismic risks, using both, deterministic and probabilistic methods. These assessment methods are also applicable to installations, such as tailings ponds. Seismic safety of large dams is also the subject of ICOLD (2016). Operational safety in view of changing climate conditions and increasing hazards from e.g. flooding and the underlying strategies for assessment are discussed in IAEA (2011).

Good practice in managing long-term risks has several complementary components. With these components one aims to capture the likely long-term development of the site and its surroundings and the likely long-term performance of engineered features, such as dams, coverings and vegetation covers. The overall objectives of closure, rehabilitation and long-term management is to re-integrate the former extractive site and the associated EWFs into the natural evolution of the surrounding area. For this reason, a good practice in managing the long-term risks aims to understand this evolution and not treat the site as a pure engineering problem. Considering these objectives, a good practice approach will have to include the dimensions discussed below. However, the extent and level of detail will strongly depend on the kind and scale of extractive operation that took place.

It has to be understood that the elements of good practice for long-term risk management are iterative in nature and their determination and implementation is not a simple linear process, at least for more complex sites with a higher risk potential. Thus, the site boundary conditions will guide the selection of suitable technical solutions for site management, but certain technical solutions can modify the boundary conditions. Likewise, technical solutions for closure and rehabilitation will influence potential after-uses of a site, while in turn a desired after-use will have certain requirements on the technical solutions. Again, the post-closure use of the site will determine whether the technical solution for making a site safe is likely to persist.

Risk assessment consists of an impact assessment based on mechanistic source-pathway-receptor models and an assessment of severity and likelihood of these impacts. Parametrisation of these models is carried out, whenever possible, in a deterministic way, but for certain aspects, such as climate change as a driver, this will have to be done in a probabilistic way.

Site models - The conceptual site model is the synthesis of the knowledge gathered and the mechanistic understanding of the processes at the site. The conceptual model helps to identify any gaps in understanding of the behaviour of the site and its interaction with the surrounding environment as well as the likely future evolution. It will guide the selection of technical solutions for closure and rehabilitation that is in line with its status as protected area, and inform eventual monitoring plans.

For the purpose of quantitative assessments and predictions, the processes captured conceptually have to be described in form of mathematical models, for instance for groundwater flow, geochemical reactions or the contaminant release (‘source-term model’). For practical purposes the mathematical models are cast into numerical models that allow to solve simultaneously the multitude of differential equations of the mathematical models.

Whether it is a detailed verbal description or has been cast into a sophisticated numerical model, the site model will allow to undertake ‘what if’-type simulations, with a view to identify the effects of drivers such as climate change, to select least intrusive mining and extractive waste management option, and the most appropriate rehabilitation option. The site model will also be used to demonstrate the resilience envelope with respect to uncertainties in site evolution due to e.g. uncertainties introduced by climate change or human behaviour. This then allows to project the evolution of (residual) risks over time and, hence, to guide monitoring programmes.

A narrative model describes the site, its properties, the chosen closure and rehabilitation solution and the rationale for the expected future site evolution. Such a narrative is appropriate for small quarries or gravel pits with little impacts during the operational period and where little future impacts are to be expected.

For sites where extensive landscaping will be required as part of the closure and rehabilitation activities, a geomorphological and surface drainage model may be appropriate (Martin Duque et al., 2019), that links the evolution to external drivers, such as rainfall patterns. Assessments and predictions of erosion rates will be required. The latter will also depend on planned re-vegetation efforts.

For sites where reactive minerals are present, either in mine workings or in the EWFs, geochemical models of varying degree of complexity may be needed. These can range from simple input-output box models to 3D coupled reactive-transport models for large and complex sites or mines.

In the case of regional dewatering, a model coupling the local hydrogeology with the regional hydrology as driver is likely needed to predict the effect of rising groundwater levels and their long-time behaviour in both, underground and open-cast mines. These models also allow to assess the effect of flooding a mine on the local and regional hydrology. These models may need to be combined with a reactive contaminant transport model in order to assess the evolution of the groundwater quality, including the generation of e.g. acid drainage and the resulting mobilisation of contaminants. Such hydro(geo)logical models will also be required to assess the effects of groundwater levels and precipitation patterns on the stability of engineered structures, such as dams.

Planning for rehabilitation and mine closure - Many of the mine closure risks identified can be proactively anticipated and managed through development of comprehensive mine closure plans that are developed and refined continuously throughout the life of a mine. These plans should inform the overall design and operation of the mine with the objective of minimising the environmental and social impacts and legacies that will be generated by the mine. If such approach has not been taken from the planning stage on, such proactive and anticipative approach can be initiated at any moment later in the life-time of an extractive operation.

Plans for mine rehabilitation should be developed and refined in parallel with the plans for mine closure. These plans should adopt international best practices such as:

- Progressive rehabilitation of disturbed areas during the life of mine (cf. Hamor et al., 2021);
- Selection of appropriate plant species to use in revegetation programmes in order to ensure rehabilitated areas integrate with the surrounding natural landscape;
- Selection of appropriate ameliorants to adjust soil chemistry to meet the needs of the vegetation to be established;
- Profiling of slope angles to natural angles that will remain stable in the long term
- Design rehabilitated landscapes as far as possible to contribute to ecosystem services required by local communities / that existed before mining;
- Consideration of climate change impacts anticipated for an area and use this information to inform the plans for rehabilitation of sites.

7 Developing a cross-referencing protocol and decision-tree

7.1 Permitting of exploration in protected areas

With a view to safeguarding our socio-economic wellbeing, it is not only important but a duty of the states towards their citizens to have a comprehensive understanding of the natural resources available at national and also EU-level. To this end the CRM-act (CRMA, 2024) mandates the EU Member States to carry out intensified (pre-competitive) exploration programmes on their territories. However, as has been discussed in Section 4.1.1, exploration can have certain environmental impacts and there may be regulatory or stakeholder objection against it, as it may eventually lead to an extractive operation. An interferences study carried out under CIRAN (Deliverable D3.2, Ovaskainen et al., 2024) concluded that there is a high probability that CRM deposits will be found under protected areas. This means that a well-founded decision-making procedure is need to support exploration programmes across the whole territory of the EU.

If carried out responsibly and with the appropriate rehabilitation measures, if necessary (say the sealing of boreholes, complete removal of drilling pads, etc.), very little or no permanent damage will be caused by exploration activities. Any impacts, however, will have to be carefully evaluated beforehand and appropriate, non- or low-invasive techniques chosen.

Considering these conditions, it will be largely normative values that guide the decision by regulators, whether to permit exploration or otherwise. Similarly, other stakeholders (local citizens, NGOs, etc.) will be guided by their respective value systems whether to oppose explorations or not. These normative debates are represented summarily by the pink box in Figure 12.

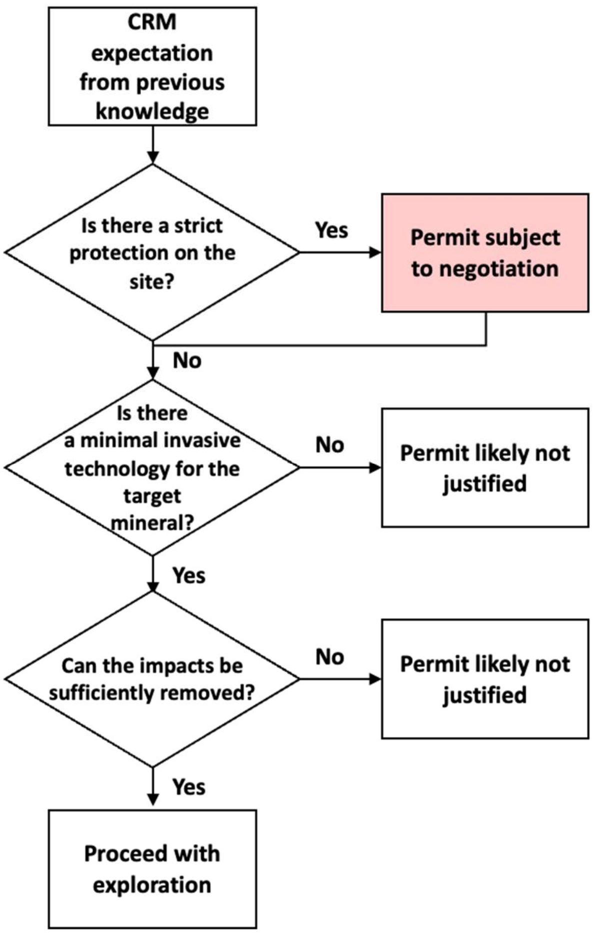

Figure 12: Basic decision-making tree for permitting exploration in protected areas.

7.2 Justification of extraction

The key question to answer by CIRAN is, under which conditions the extraction mineral raw materials underneath a protected area and the associated disturbances at the surface may be justified. There should be no need to justify per se geological mapping and prospecting projects, as it can be considered a justified task of governments to inform themselves about the natural resources available to provide for the well-being of its citizens. In addition, an assessment of such mineral occurrences that are considered critical for the EU economy is now mandated by the 2024 CRM-Act (CRMA, 2024). Conversely, extraction projects in protected areas require a careful weighing and evaluation of all the pros and cons, of the benefits and detriments associated with them against other societal needs and expectations.

Such a weighing and evaluation have to be carried out at different levels, at EU level, at national level and at regional and site level. There must be an overriding public interest, such as ensuring supply security, and not only the commercial interest of an operator. For this multi-level evaluation, a set of tools are proposed.

At site or project level the UNFC assessments discussed in Section 5.1 are a tested instrument. This, however, has to be embedded into a framework that allows to evaluate, whether there is an overriding public interest in extraction and what factors drive this interest. Often, environmental protection is *a priori* considered to be of overriding interest. Thus, the tool must be capable to balance against each other the different factors of public interest in order to decide, which should be the overriding one. Given these requirements for a comprehensive assessment tool, the Drivers-Pressures-States-Impacts-Response (DPSIR) framework emerges as a particularly suitable approach (Figure 13).

The DPSIR framework was championed in the early 1990s by the European Environment Agency (EEA, https://www.eea.europa.eu/) to understand and eventually phase out the use of certain metals and chemical compounds that were considered to be detrimental to the environment and human health (Smeets and Weterings, 1999). Conversely, the DPSIR-framework can be used to understand the drivers behind mineral raw materials needs and to assess them, whether they may constitute an overriding public interest.

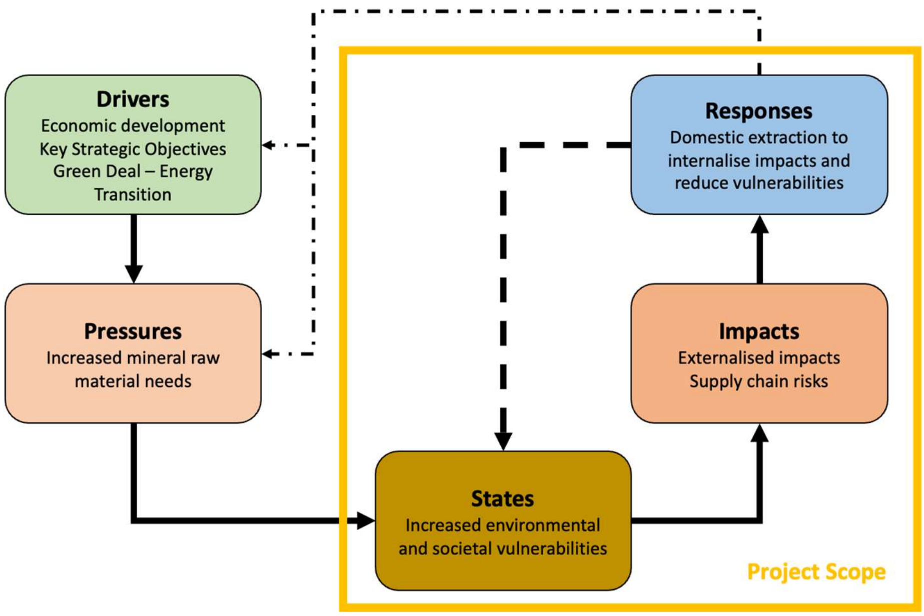

Figure 13: Conceptual DPSIR-framework for understanding the need for domestic extraction.

During a permitting process, regulators can identify the driving forces and resulting pressures. The relevance of indicators from the DPSIR framework for regulators varies depending on the stage of the project. In the initial stage of permitting, indicators on the state of the environment and impacts are crucial to assess the effectiveness of environmental protection measures and to identify unwanted consequences.

Thus, the DPSIR-framework can provide a rationale for the justification of extraction in protected areas or otherwise. Developing this framework for a given case will be an iterative procedure that takes into consideration the (natural) values to be protected, the mining technology options and their likely associated environmental impacts, the extractive waste management solutions, the resulting unavoidable overall impacts as well as the regulatory and (local) societal context. While the ultimate decision whether to mine or not in a protected area will be a judgement of the relative societal value of access to primary raw materials vs. nature protection, it will take place in a certain socio-political context that determines the societal needs for these mineral raw materials.

The process of justification requires a decision tree that incorporates both elements, a higher-level assessment of public interest on the basis of the DPSIR-framework and a site-level assessment according to UNFC whether the necessary conditions according to the E-, F-, and G-axes (cf. Section 5.1.3) are fulfilled. In fact, already the DPSIR assessment will need to be undertaken for each mineral separately, even for sites, where more than mineral would be extracted. There may be sufficient justification for extraction, if one of the minerals mandates this, while the others may not even be CRMs. Conversely, if a CRM is only a minor contribution to the overall extraction of others, the project may not be justified.

In the following, such a decision-tree is discussed from an operational perspective, while CIRAN Deliverable D6.2 (Hilton et al., forthcoming) illuminate the subject from a social science perspective, in particular with respect to societal preferences in the context of options assessment.

Given the considerable time-lag between filing an application for permit to extract and the first product delivered to the market, In the DPSIR analysis also the likely development of future demands will need to be considered. This may need to be done on a ten-year or so time horizon. To this end horizon scanning and Delphi-methods are being proposed in CIRAN D3.3 (Lopez et al., forthcoming). The aim of such future scenarios studies is to avoid extraction projects under or near protected areas that may have become superfluous by the time they come on-line.

A three-tier decision-making process (with some iterations) is proposed: the first level will be the determination whether there is an overarching public interest (in the DPSIR-framework outlined above), the second level assesses, whether it can be done economically, and the third level determines, whether it can be done in a way that is compatible with the protected status of the area, i.e. the actual permitting process per se as outlined below.

7.3 Performance evaluation

The performance evaluation of extractive operations beneath protected areas must be as rigorous and systematic as the initial decision-making process. Building on the DPSIR framework and drawing from the risk catalogues presented in Appendix I, we propose a structured performance monitoring system that tracks impacts across three key dimensions: environmental performance indicators derived from baseline ecosystem functions, technical performance metrics linked to the selected mining methods, and socio-economic indicators reflecting stakeholder concerns. This monitoring framework needs to be adaptive, recognising that certain impacts may only become apparent over time and that the sensitivity of protected areas may change with evolving climatic conditions or cumulative pressures. The evaluation system should incorporate both quantitative measurements and qualitative assessments from stakeholders, particularly regarding aspects such as visual impact and ecological integrity that may not be fully captured by numerical indicators alone.

The practical implementation of performance evaluation requires establishment of clear thresholds and trigger points for adaptive management responses. These should be derived from the initial environmental impact assessment but remain flexible enough to accommodate new understanding as operations progress. For example, groundwater monitoring might begin with standard measurements of water table levels and quality but should be capable of expanding to include newly identified parameters or locations if unexpected impacts are detected. Performance evaluation should also assess the effectiveness of mitigation measures and the accuracy of impact predictions made during the permitting phase, creating a feedback loop that improves future decision-making. Regular review periods should be established where operational permits can be reassessed based on actual performance data, with clear procedures for implementing additional controls or ultimately withdrawing permits if performance consistently falls below acceptable thresholds. This approach ensures that the careful balancing of interests achieved during the initial decision-making process continues throughout the operational phase of the project.

7.4 Operationalisation of decision-making

7.4.1 The hard facts - economic evaluation

As has been discussed in Section 5.1, the economic assessment is carried out using either the CRIRSCO resource assessment or the UNFC resource classification, sometimes also both. The UNFC (cf. Section 5.1.3) was developed to standardise the classification and reporting of fossil fuel and mineral reserves and resources. Over time, it has evolved to encompass a wider range of natural resources, including renewable energy. In this context, the application of the UNFC (UNECE, 2022a) on geothermal projects, proposes a detailed decision-making tree for each of the 'axes' during the evaluation of resources (Figure 14 to Figure 16). As the decisions depend on each 'product', i.e. each extracted commodity, it will need to be repeated for each of them (see EGRM, 2024).

For each of the three axes (E, F and G), a separate decision tree is provided. By following the arrows from decision box to decision box, the user will end up in a box giving the most suitable classification at the highest hierarchical level for the given axis.

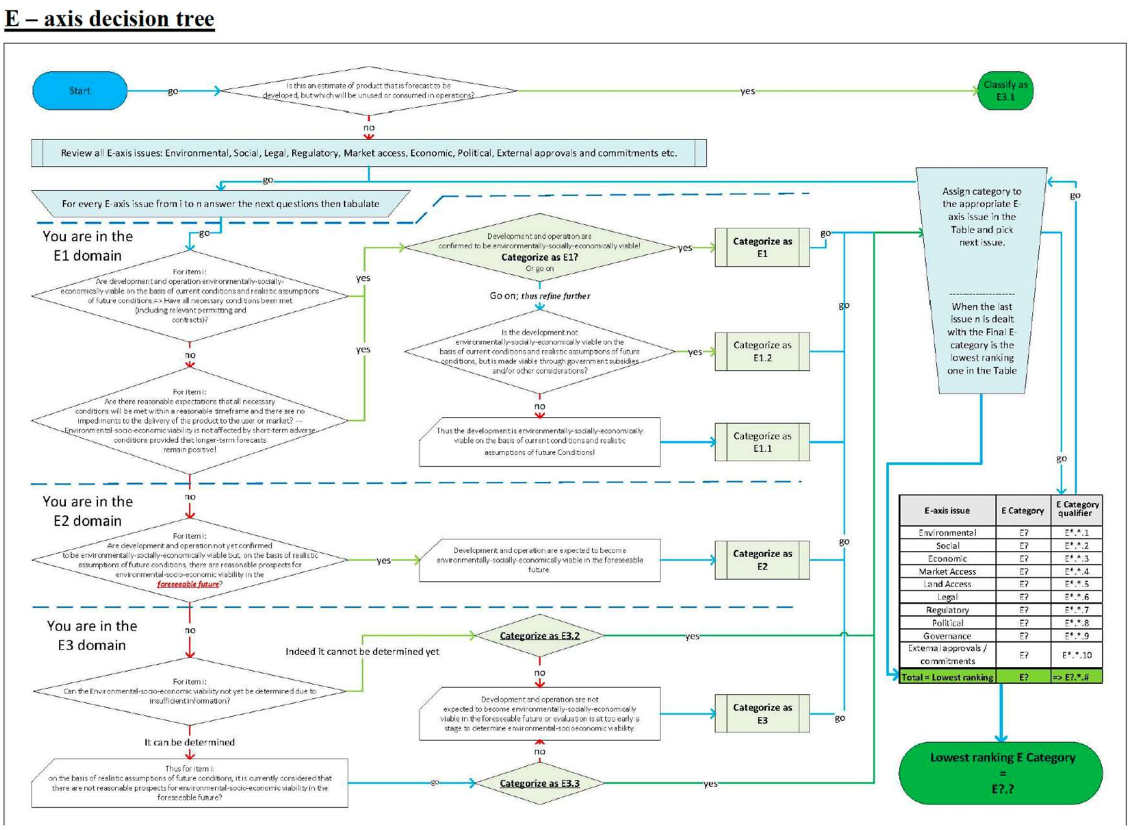

Figure 14: UNFC E-axis decision-making tree (UNECE, 2022a).

F – axis decision tree

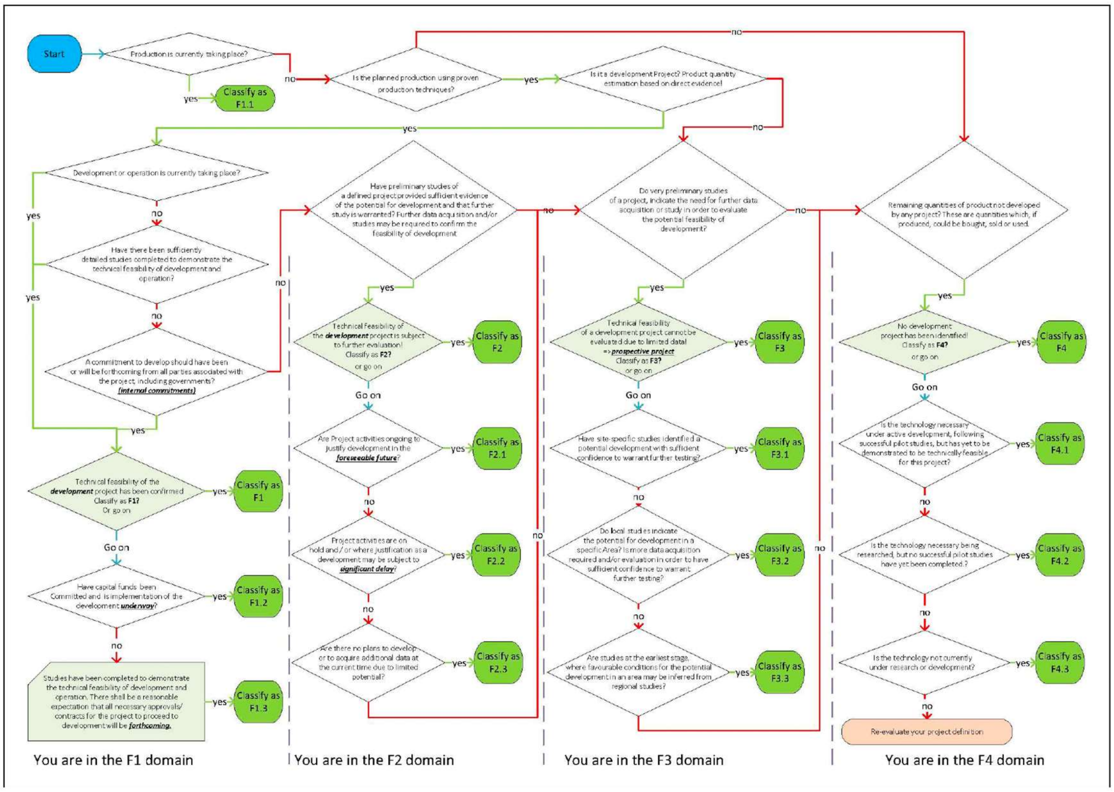

Figure 15: UNFC F-axis decision-making tree (UNECE, 2022a).

G – axis decision tree

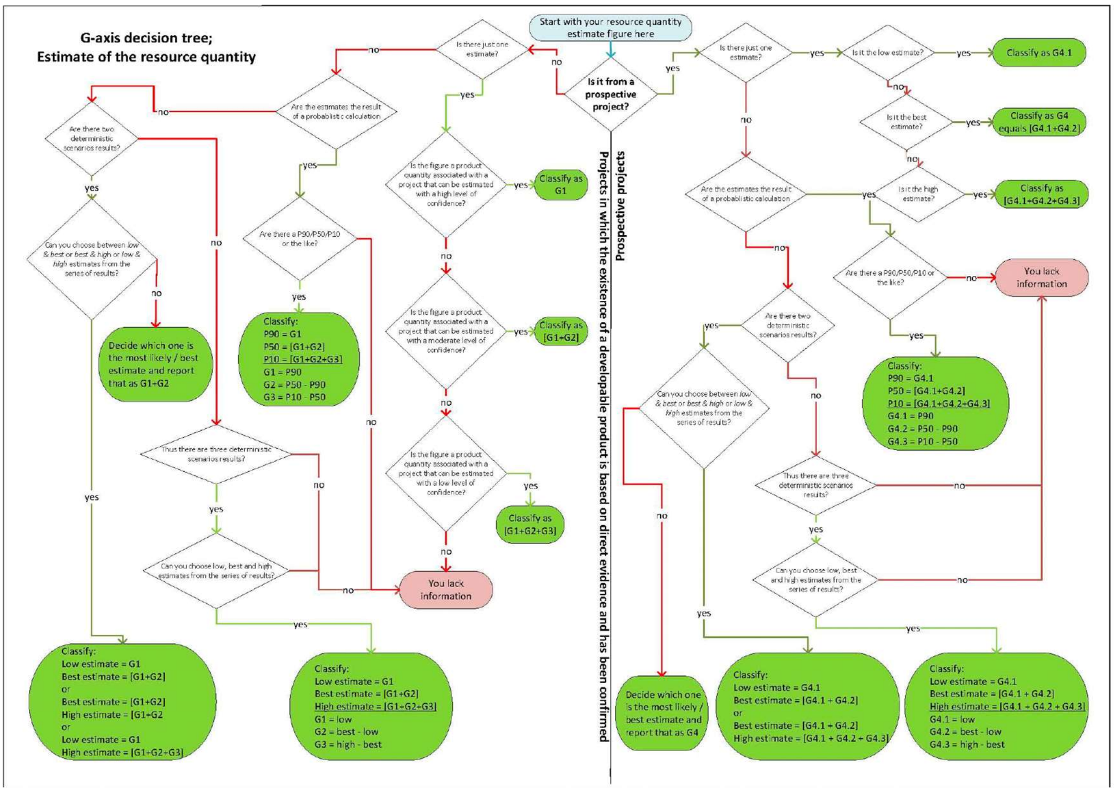

Figure 16: UNFC G-axis decision-making tree (UNECE, 2022a).

However, in the case of finding sufficient justification for permitting an extraction project beneath a protected area, in particular the E- and the F-axes are not independent from each other. The optimisation of the extraction technique, which is subject to an assessment according to the F-axis may be bounded by requirements imposed by the need to absolutely minimise environmental impacts at the site *per se* and also by regulatory and stakeholder preferences. This in turn may determine the amount of recoverable resource and thus will have repercussions on the assessment according to the G-axis. It is likely, that some iteration steps in this assessment will be required. To some degree this is already foreseen in the decision tree of UNFC (UNECE, 2022a) by introducing a loop into the E-axis, because there is potentially a suite of issues pertaining to the 'license to operate' in the environmental, social, economic, legal, etc. domains, that need to be resolved (see also the work in CIRAN WP6). There will usually be multiple contingencies and the overall project E-classification should be that of the lowest ranking one.

While in principle the evaluation according to UNFC needs to be carried out for each target commodity separately, there will be many common elements along the decision trees (Figure 14 to Figure 16).

Overall, the purpose of the evaluation according to UNFC is to confirm, that there is a business case in principle for the mining project, assuming that all the issues of the E-axis can be resolved. UNFC (UNECE, 2022a) treats these issues only summarily and in the following a decision-making scheme for the special case of extraction underneath a protected area will be developed. As a starting point, mineral occurrences underneath protected areas would be classified as 'inventory' (E3F2, in Sub-categories E3.3, F2.3) where the quantities are technically recoverable, but are not expected to become environmentally-socially-economically viable in the foreseeable future (UNECE, 2024), unless the permitting issue can and needs to be resolved under pressure of societal needs.

7.4.2 Integration of DPSIR-frameworks and UNFC evaluations

A UNFC evaluation will provide the basis for initiating permitting procedures for extraction in protected areas. Without a positive economic and technical evaluation that demonstrates that a project would be viable, there would be no point in proceeding towards a permitting procedure. It remains, however, to be demonstrated that there is an overriding public interest in favour of mining vs. absolute environmental protection. The societal need for mineral raw materials has to be weighed in a structured way against the societal need for environmental protection.

As was discussed at the beginning of the chapter, it appears that a decision-finding process that is framed by the DPSIR concept would be the most appropriate one. On this basis an operational decision-making tree is developed below.

The decision, whether to permit extraction under those circumstances involves a considerable number of value- and norm-driven judgements. The decision-making scheme helps to frame and make transparent these judgemental aspects. CIRAN Deliverable D6.2 (Hilton et al., forthcoming) delves deeper into this aspect.

It is important to recognise that there are various fundamentally different responses to the policy-driven demand for increasing amounts of mineral raw materials. Certain societal groups may fundamentally question the development trajectory implied by the EU-policy decisions and thus the need for increasing amounts of mineral raw materials). The EU itself proposes in the CRMA (2024) multiple response strategies to possible supply risks, that include among increased EU domestic mining also bilateral supply agreements with 'friendly' nations, effectively externalising possible environmental and societal impacts. The other two response options and the time horizon of their efficacy is being discussed in CIRAN deliverable D3.3 (Lopez et al, forthcoming) in more detail. It is, however, unlikely that in the near future recycling and substitution will have a significant impact on the predicted demands of certain CRMs, such as lithium, cobalt or graphite.

Figure 17 outlines and assessment of policy-driven demand and its effect on the decision to permit extraction or otherwise. In the first step a demand is observed, which then is analysed with respect to the underlying drivers, e.g. whether the demand is caused by certain EU policy-decision, such as the phasing out of fossil fuels. In other words, if the mineral in question is not declared a CRM, a mining permit will not be justified. A second tier of assessment will have to look at the overall availability of that CRM from sources within

Europe. If there are alternative locations that are not in protected areas, it is unlikely that a project in a protected area would be justifiable. Based on the knowledge of the occurrence gathered through exploration an initial decision will have been made, whether the resource is likely to have a commercially viable size and whether it could be mined economically. In the following step, the viability in the UNFC E-axis has to be assessed.

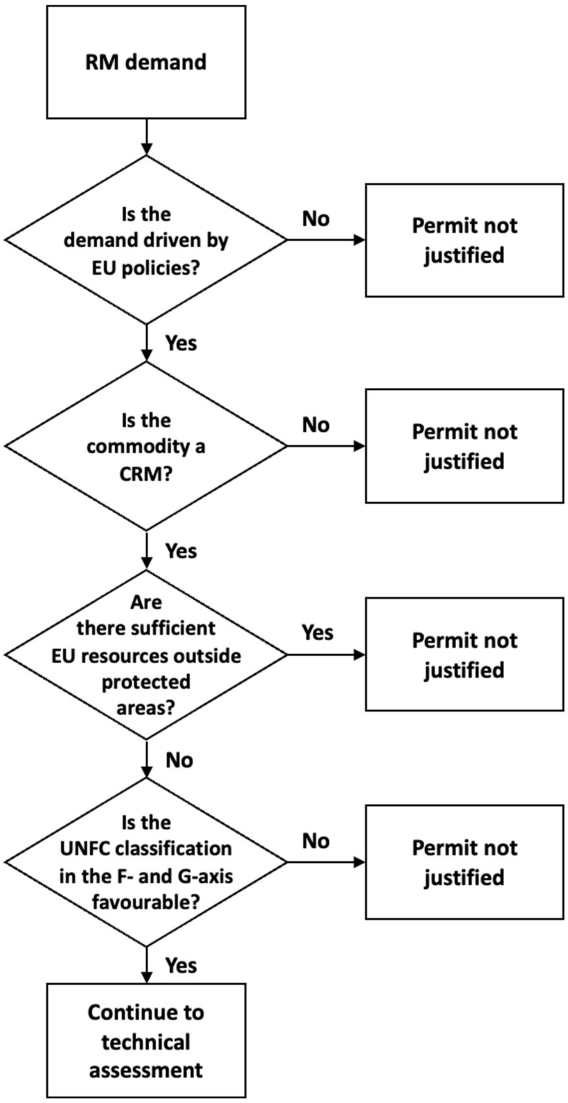

Figure 17: Decision scheme for elucidating policy-driven demand and project viability.

This decision-making process has to respond to a number of questions, including:

- At what level and under what regulatory control is the protection exercised: local, Natura 2000, UN Heritage, etc., i.e. legally binding or international agreements?
- Which are the actual values to the protected?
- How and what natural values would actually be affected by the mining operation?
- Would exemptions due to ‘emergencies’ be possible and under what conditions?
- The decision-making has to consider the whole life-cycle, i.e. to what conditions can the mine and extractive waste management sites by remediated and what lasting changes in the protected area will result?
- Is ‘compensation’ for loss of natural value (e.g. at Natura 2000 sites) possible and when has this to be put in place (before, during, after) the mining operation?

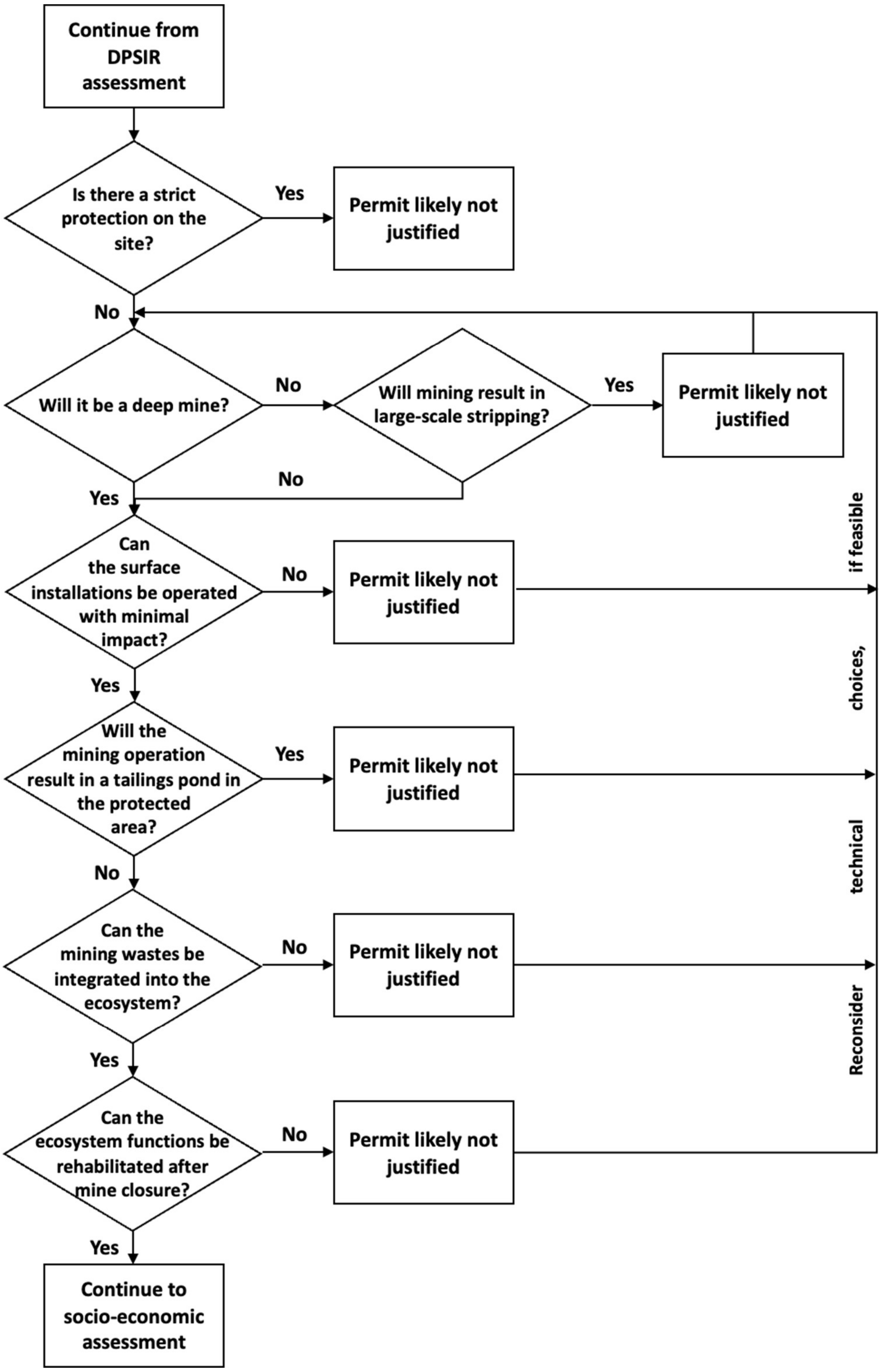

Figure 18: Decision-scheme the technological assessment.

Due to the necessarily iterative and recursive nature of some of the decision-finding processes, it is not so obvious, where to start a decision-making tree. The starting point will depend on the kind of decision process in which it may be used. One could envisage, for instance, to make decisions in principle, whether in areas of potential conflict any exploration or a mining permitting process could be initiated vs. an 'absolute' protection under any circumstance. Such delineation can help saving time and financial resources, as these would not be wasted on areas, where neither exploration nor extraction would be permitted. To this end the decision-finding tree should begin with the nature of the site and the kind of its protection. If there is an 'absolute' protection, the process would stop right there (cf. Figure 18).

While it is quite easy to build practical decision-making trees, many of the key decisions are actually decisions about normative values and their respective weight. The decision to protect a site is based on the normative values of our societies at national or international level. As societies evolve, their needs and norms evolve, so that there may not be a truly 'absolute' values. The stakeholder discussions under CIRAN WP5 are undertaken to better understand people's normative values in cases of having to make difficult choices and having to decide between environmental protection and fulfilling societal needs. The wider societal implications are elucidated in the work under WP6.

In the following, a decision-tree for the feasibility of extraction is proposed, but without discussing the societal, regulatory, or administrative processes that will govern the decision-making itself. The focus is on administrative and technology-related decisions in order to determine the feasibility of extraction, without deciding on the desirability, which is treated in Figure 17. It is assumed that through previous exploration programmes sufficient information is available to inform this decision tree.

Figure 18 outlines the decision-making process from the point of view of mining strategy or technical choices that would permit mining with minimal lasting impacts in the protected areas. It is important to note that there may be iterative or recursive steps along the assessments, as the strategy or technology choices may be changed or adapted to minimise impacts and fulfil regulatory or stakeholder expectations. Changing the mining strategy (e.g. deep vs. open-cast mining, or access by shaft from within the protected areas vs. incline from the outside, possible rehabilitation measures, etc.) will have economic implications, which in turn will affect the viability of a project. This aspect will be treated in a (re-)assessment of the resource classification according to UNFC or through CRIRSCO-compliant reporting respectively (see Section 7.4.1). Also, stakeholders and regulators may have preferences for certain strategic and technical solutions or reject them. Such preferences or rejections may be based on norms and values of the respective stakeholders, rather than on technological knowledge, an aspect that is further illuminated by CIRAN WP5.

7.5 Integration of decision-making processes across regulatory regimes

The decision-making process according to Figure 18 takes place in the context of multiple sets of regulations that fall typically under the remit of different and sometimes competing regulatory bodies, such as the environmental regulators, the water resources regulators, spatial planning or economic development authorities, or those concerned with the preservation of cultural heritage. Depending on Member State, these regulators may be at different levels of government, sometimes at national, in other cases at provincial (e.g. Länder in Germany, Préfecture in France) or even at municipal level (e.g. for spatial planning). CIRAN deliverable D3.1 (Barnes and Berne, 2024) shed light on this complex situation in a selection of Member States that is illustrated by the bow-tie diagram in Figure 19.

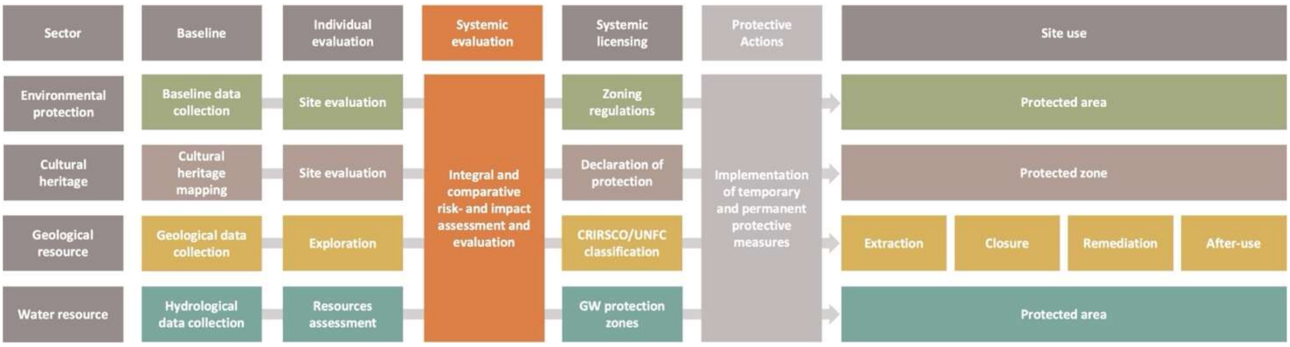

Figure 19: Bow-tie diagram illustrating the complex and sometimes competing realms of different regulators.

Barnes and Berne (2024) discuss, where the 'node' could be in which the different regulatory decision-making procedures could come together in the selected Member State in order to achieve a decision-making that balances the different societal needs.

7.6 The dimension of time

It needs to be remembered that the EU list of 'critical raw materials' (CRMA, 2024) continuously evolves with planned updates every three years. One of the reasons is that technology, markets and the geopolitical situation as the main drivers evolve. Set against this are the lead-times from the beginning of exploration, the discovery of a resource and the eventual permitting, which can be one or more decade realistically. The time-lines foreseen by the CRMA (CRMA, 2024) for an accelerated permitting seem to be rather optimistic for this particular situation, considering the careful EIA and the negotiations between different (regulatory) stakeholders required. Once the permit is given, the detail planning required and actual mine construction mean that it may take another two to three years before the first commodity can be on the market. In summary, it may take two or more revision cycles of the CRM list, before a mine can be actually on line.

At the same time, technology development in the areas of, for instance, batteries and magnets, progresses rapidly. As a consequence, it may well be that certain metals that are on the top of the list today, will become less important over a ten- or 20-year time horizon. This in turn will have repercussions on justification of certain mines underneath a protected area. Other metals, such as copper, will remain critical regardless of the actual scenario. The scenario analyses of the CIRAN deliverable D3.3 (Lopez et al., forthcoming) aim to give some perspective to this question that also will be an ethical and normative one.

The conclusion may well be, that given the technological advances in mining strategies and techniques in the area of low-visible and low-impact mining, that such operations at depth may well be compatible with a surface status of protected area.

7.7 Site-specific environmental values

The integration of site-specific environmental values into the decision-making protocol requires a nuanced understanding of both the protection status and the actual ecological functions being safeguarded. As detailed in Chapter 2, these values range from biodiversity and habitat preservation to ecosystem services and cultural heritage. Our analysis shows that the mere presence of a protection designation is insufficient for decision-making; rather, the specific natural values being protected must be mapped against potential impacts from different mining configurations and technologies. For instance, a deep mine beneath a protected area designated primarily for its surface biodiversity may be more acceptable than one beneath an area protected for its geological features or hydrological functions that could be impacted by subsurface activities.

The decision-making protocol therefore incorporates environmental values at three critical stages: initial screening, detailed assessment, and operational planning. At the screening stage, the protocol requires explicit identification and categorisation of protected values according to their sensitivity to different types of mining impacts, using the comprehensive framework outlined in Section 2.2. The detailed assessment phase then evaluates specific impact pathways between proposed mining activities and these identified values, considering both direct effects and potential cumulative impacts. Finally, the operational planning stage requires demonstration that mining methods and technologies have been specifically selected and adapted to protect the identified values, with clear thresholds for acceptable impact established through stakeholder consultation. This systematic integration of site-specific environmental values ensures that decisions about mining beneath protected areas are grounded in actual ecological and conservation requirements rather than arbitrary designations.

8 Conclusions

This report reviews the mid- to long-term environmental and societal impact of extractive activities in environmentally protected areas comparing expected outcomes during design and permitting stages with actual implementation experiences. A particular focus is placed on identifying and understanding performance gaps to improve future decision-making processes.

Analysis of case studies from CIRAN Deliverable D2.1 (Luodes et al., 2024) reveals three significant areas where actual impacts frequently exceed initial predictions: groundwater management, with draw-down effects extending beyond modelled zones and causing unexpected ecosystem impacts; noise and vibration propagation affecting wildlife behaviour over larger areas than anticipated; and habitat fragmentation from transport infrastructure, often amplified by cumulative effects with other regional developments. Successful operations consistently demonstrate the need for more extensive monitoring than initially planned, allowing early detection and mitigation of unexpected impacts. These findings emphasise the importance of conservative impact predictions and adaptive management strategies in project planning and implementation.

Based on these insights, a decision-making tree in several stages was developed, that aims to develop an understanding, whether extraction underneath protected areas may be justified to fulfil societal needs other than that for protecting a specific piece of environment. The decision-tree aims to make transparent the drivers behind proposals to extract mineral resources from underneath protected areas using a DPSIR model. In this way the relative urgencies of societal needs are balanced in a transparent way.

Whether extraction from underneath protected areas can be done with limited environmental impact depends critically on the extraction strategy and technology used. This aspect feeding into the decision-tree has been more deeply reviewed in CIRAN Deliverable D4.1 (Carriedo et al., 2024). These extraction methods may be also subject to a stakeholder value-driven assessment from an environmental and societal perspective. Thus, general public and regulatory authorities will probably also give preference to extraction strategies and technologies that result in the least visibility and disturbance at the surface, if they consider at all extraction from beneath protected areas.

Stakeholders, including permitting authorities and the general public, may consider risks and impacts over different time-scales, covering the whole life-cycle of an extractive operation, from the construction of an extractive facility and its infrastructure to closure, rehabilitations and possible constraints on the rehabilitation and after-use of such sites.

In addition, in a systemic and comprehensive environmental assessment, other impacts and risks, such as health & safety risks to workers, communities, and risks natural ecosystems have been taken into consideration. To this end, a catalogue of potential risks was developed, based on the guidance by the European Commission on the management of extractive waste (c.f. MWEI-BREF, 2018) and on its forthcoming guidance on risk assessment in the extractive industries.

On the other side, the dimensions to be taken into account in the assessment of implications of CRMs extraction from beneath environmentally protected areas have been defined, considering nature conservation factors (e.g., natural values protected), and the given geological settings (e.g., type and characteristics of CRMs' deposits). This allows to appropriately cross-reference natural values protected/to protect, the drivers behind societal CRMs needs by framing it in a DPSIR (Drivers-Pressures-States-Impacts-Response) model and extraction methods and technologies, at the earliest stage of permitting procedures.

Considering the longer-term societal and environmental impacts, in most cases one can make only hypotheses, when the period extends beyond a few years. Both, societal and environmental ecosystems are complex systems and also depend on the development in the wider surroundings. In addition, impacts are not always negative. Increased economic activity in a region will also generate tax income, from which more protection of the environment can be funded. Likewise, in some cases, particularly in the case of open-cast mines, the presence of lakes after closure and rehabilitation has increased the biodiversity. This, however, has to be viewed considering the relative rarity of the protected area in question. There may be certain types of specific ecosystems a man-made increase in biodiversity may not be desirable, because it disturbs the uniqueness of the existing ecosystem. In case of brown-field mining in areas that have been previously disturbed by mining, but since have been declared protected areas, the income generated from mining can also help to further rehabilitate affected lands.

A key aspect in the decision-making process is land use planning and its flexibility as a function of societal urgencies, which has to be reflected in the decision-tree by introducing recursive loops.

On this basis, a decision-making protocol is proposed that allows to adequately evaluate and balance the potentially conflicting societal expectations and needs between environmental protection and providing for a sustained socio-economic development.

9 References

APEC Asia-Pacific Economic Cooperation (2018): Mine Closure. Checklist for Governments.- Report APEC#218-SO-03.1: 96 p., https://www.igfmining.org/wp-content/uploads/2019/04/218_MTF_Mine-Closure_Checklist-for-Governments-1.pdf (accessed 15.11.24).

Barnes, J., Berne, S. (2024): Fitness-for-Purpose Assessment of Regulatory Frameworks.- Deliverable 3.1 of the Critical raw materials extraction in environmentally protected areas (CIRAN) project, Grant Agreement No. 101091483 of the European Union's Horizon Europe research and innovation programme: 142 p.

BioMOre (2018): New Mining Concept for Extracting Metals from Deep Ore Deposits using Biotechnology.- CORDIS, https://cordis.europa.eu/project/id/642456 (accessed 23.12.24).

Carriedo, J. et al. (2024): Catalogue of emerging low-impact, low-visibility extraction methods.- Deliverable 4.1 of the Critical raw materials extraction in environmentally protected areas (CIRAN) project. Grant Agreement No. 101091483 of the European Union's Horizon Europe research and innovation programme.

Carvalho J.M.F., Meira J., Marques C., Machado S., Mergulhão L.M., Cancela J. (2016): Sustainable exploitation of mineral resourceswithin an area of the Natura 2000 network. European Geologist J., **41**: 11–15, https://eurogeologists.eu/european-geologist-journal-41-sustainable-exploitation-of-mineral-resources-within-an-area-of-the-natura-2000-network/ (accessed 20.11.24).

C&E Consulting & Engineering GmbH (2021): Guidelines for Mine Closure Activities and Calculation and Periodic Adjustment of Financial Guarantees.- Report on the "Study on the elaboration of guidance on best practices for the calculation and the periodic adjustment of the financial guarantee for extractive waste facilities", European Commission, Contract 07.201/2018/793585/ETU/ENV.B.3: 215 p., https://op.europa.eu/de/publication-detail/-/publication/cdb0af5d-8b8d-11eb-b85c-01aa75ed71a1/language-en.

CEU Council of the European Union (1989): Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work.- OJ 183/1-183/8 of 26.06.89, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31989L0391&from=EN.

CEU Council of the European Union (1992): Council Directive 92/91/EEC of 3 November 1992 concerning the minimum requirements for improving the safety and health protection of workers in the mineral-extracting industries through drilling (eleventh individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC).- OJ L348/9-24, 28.11.92, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31992L0091&from=EN.

CEU Council of the European Union (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive).- OJ L 327/1-73, 22.12.2000, https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF

CEU Council of the European Union (2006): Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).- OJ L 396/1-520, 30.12.2006, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006R1907-201404 10&from=EN.

CEU Council of the European Union (2006): Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE).- OJ L 108/1-14, 25.4.2007, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0002.

CEU Council of the European Union (2014): Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment.- OJ L124/1-18, 25.04.2014, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0052.

Cravo R., Guerreiro J. (2019): Environmental Sustainability: A 30-Year Progress Assessment in Portugal.- J. Environmental Protection, **10**(11): 1507-1535, https://doi.org/10.4236/jep.2019.1011090.

CRIRSCO and UNECE (2024): Guidance Note to the use of the CRIRSCO Template-UNFC Bridging Document. Document prepared by the joint CRIRSCO-UNECE Ad Hoc Task Group for Revising the CRIRSCO Template and UNFC Bridging Document. Draft approved by the CRIRSCO Executive and the Expert Group on Resource Management's Technical Advisory Group in November 2023.-https://www.crirsco.com/; https://unece.org/sustainable-energy/sustainable-resource-management/unfc-documents.

CRMA European Parliament and Council (2024): Regulation (EU) 2024/1252 of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020.- OJ L Series, 03.05.24, 67 p., https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401252 (accessed 24.09.24)

de Groot, R., van der Perk, J., Chiesura, A., Marguliew, S. (2000): Ecological Functions and Socioeconomic Values of Critical Natural Capital as a Measure for Ecological Integrity and Environmental Health.- Ch. 20 in: Crabbé, P., Holland, A., Ryszkowski, L., Westra, L. [Eds.], Implementing Ecological Integrity. Nato Science Series, 1: 191–214, Dordrecht (Springer), https://doi.org/10.1007/978-94-011-5876-3_13.

de Groot, R.S., Wilson, M.A., Roelof M.J Boumans, R.M.J. (2002): A typology for the classification, description and valuation of ecosystem functions, goods and services.- Ecological Economics, **41**(3): 393-408, https://doi.org/10.1016/S0921-8009(02)00089-7.

Dudley, N. (Ed.) (2008): Guidelines for Applying Protected Area Management Categories. With Stolton, S., Shadie, P., Dudley, N. (2013): IUCN WCPA Best Practice Guidance on Recognising Protected Areas and Assigning Management Categories and Governance Types, Best Practice Protected Area Guidelines Series No. **21**: X+86+IV+10 p. Gland, Switzerland (IUCN), https://portals.iucn.org/library/sites/library/files/documents/pag-021.pdf (accessed 14.11.24.

Endl, A. et mult. al. (2019): Final Manual for Good Practice Guidance.- H2020 Project MinLand, Deliverable D6.2: 216 p., https://www.minland.eu/wp-content/uploads/D6.2_Final-Manual_final-online-submission_6-12-2019.pdf (accessed 23.12.24)

Eco-Efficiency Consulting and Engineering Ltd., WEFalck, Satarla, Afry Finland Oy, CRS Ingenería, Geologia e Geotecnia Consultores Lda., Andreev, I., Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI, Total Business Land (2023): Study supporting the elaboration of guidelines for best risk management approaches in the extractive sector.- Study carried out for the European Commission (DG-ENV) under Contract No 070201/2019/818015/ETU/ENV.B.3, awaiting publication.

Erdmann, L., Moller, B., Tercero Espinoza, L.A., va Oers, L., Bisevac, V., Correia, V., Delfini, C., Thorsøe, K., Falck, W.E., Petavratzi, E., Lauinger, D., Radwanek-Bak, B. Arnbom, J.-O. (2017): Stakeholder Needs.- H2020-Project MICA, Deliverable D2.2: 78 p., www.mica-project.eu.

European Commission (Directorate-General for Environment), Eco Efficiency Consulting and Engineering Ltd., WEFalck, Kertész, B., Pöyry Finland Oy, CRS Ingenería (2019): Development of a guidance document on best practices in the extractive waste management plans. Circular economy action – Study.- 59 p., https://ec.europa.eu/environment/waste/mining/pdf/guidance_extractive_waste.pdf

EWD European Parliament and Council of the Europe Union (2006): Directive 2006/21/EC of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC.- OJ L 102/15-33, 11.04.2006, https://eur-lex.europa.eu/resource.html?uri=cellar:c370006a-063e-4dc7-9b05-52c37720740c.0005.02/DOC_1&format=PDF (accessed xx.xx.24)

Falck, W.E. (2016): Integrating Decommissioning and Environmental Remediation into the Life-Cycle Management of Mining and Milling Sites.- Euromines Newsletter, 3/2016: https://euromines.org/files/newsletter2016_3s.pdf (accessed 25.03.24).

Falck, W.E., Hejny, H., Spangenberg, J.H., Wittmer, D. (2014): Stakeholder Engagement to Achieve Social-Licensing for Novel Technologies in Mine-Site Development – Applying Lessons-Learnt from EO-Miners to

I²Mines.- In: Martens, P.N. (Ed.) High-Perfomance Mining', Aachen International Mining Symposia, Aachen, Germany, 11-12 June 2014, AIMS Vol. **13**: 611-620.

Falck, W.E., Spangenberg, J.H. (2014): Selection of Social Demand-Based Indicators: EO-based Indicators for Mining.- J. Cleaner Prod., **84**: 193-203, http://www.sciencedirect.com/science/article/pii/S0959652614001656.

Gabrielsen P., Bosch, P. (2003): Environmental Indicators: Typology and Use in Reporting.- EEA internal working paper: 20 p., Copenhagen (European Environment Agency EEA), http://costabalearsostenible.es/ATenpdf/2.Hor/Sistemaindicadores/Key%20References_Indicators/EEA%202003.pdf (accessed 14.11.24).

GlobalTailingsReview.org (2020): Global Industry Standard on Tailings Management.- https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf.

Hamor, T., Vidal-Legaz, B., Zampori, L., Eynard, U., Pennington., (2021): A review of European Union legal provisions on the environmental impact assessment of non-energy minerals extraction projects.- https://op.europa.eu/en/publication-detail/-/publication/0dd9ea0c-d953-11eb-895a-01aa75ed71a1/language-en/format-PDF/source-229039161.

ICMM International Council on Mining and Metals (2006): Good Practice Guidance for Mining and Biodiversity.- 142 p., https://www.icmm.com/website/publications/pdfs/environmental-stewardship/2006/guidance_mining-biodiversity.pdf (accessed 14.11.24).

ICMM International Council on Mining and Metals (2019): Integrated Mine Closure – Good Practice Guide, 2nd Edition.- 132 p., https://www.icmm.com/website/publications/pdfs/closure/190107_good_practice_guide_web.pdf (accessed 15.11.24).

ICMM International Council on Mining and Metals (2020): Key Performance Indicators – Tools for closure.- 7 p., https://www.icmm.com/en-gb/guidance/environmental-stewardship/2020/kpi-tool-for-closure#:~:text=This%20tool%20provides%20a%20set,practices%20at%20an%20operational%20level (accessed 15.11.24).

IAEA International Atomic Energy Agency (2002): Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium.- IAEA, Vienna, Safety Reports Series **27**: 65 p., https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1146_scr.pdf (accessed 15.11.24).

IAEA International Atomic Energy Agency (2006): Management of Long-Term Radiological Liabilities: Stewardship Challenges.- IAEA, Vienna, Report IAEA-TRS-450, 224 p., http://www-pub.iaea.org/MTCD/publications/PDF/TRS450_web.pdf (accessed 15.11.24).

IAEA International Atomic Energy Agency (2010): Seismic Hazards in Site Evaluation for Nuclear Installations.- IAEA Safety Standards Series, SSG-9: 56 p., https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1448_web.pdf (accessed 15.11.24).

IAEA International Atomic Energy Agency (2011): Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations.- IAEA Safety Standards Series, SSG-18: 146 p., https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1506_web.pdf (accessed 15.11.24).

ICOLD International Commission on Large Dams (2016): Selecting seismic parameters for large dams. Guidelines.- ICOLD Bulletin 148: 72 p., https://www.icoldchile.cl/boletines/148.pdf (accessed 15.11.24)

IUCN International Union for Conservation of Nature (2024): Guidelines for Using the IUCN Red List Categories and Criteria, Version 16 (March 2024).- 122 p. https://nc.iucnredlist.org/redlist/content/attachment_files/RedListGuidelines.pdf (accessed 14.11.24).

Leoni G., De Caterini G., Vizzini G., Assennato F., Bianco P.M., Decorso C., Delfini C., Ferrigno F., Finocchiaro G., Fumanti F., Guerrieri L., Lucarini M., Roggero F., Tria N.G., Spizzichino D. (2024): GIASONE: a method to assess sustainability of georesources cultivation.- Abstract, Congresso congiunto SGI-SIMP - Geology for a sustainable management of our Planet, Società Geologica Italiana ETS, Roma 2024, https://doi.org/10.3301/ABSGI.2024.02.

Luodes, N. et mult. al. (2024): Description of good-practice case studies.- CIRAN Deliverable D2.1: 167 p.

MAC Mining Association of Canada (n.d): Towards Sustainable Mining Mine Closure Framework. TSM 101, A Primer.- 19 p., https://mining.ca/wp-content/uploads/2019/02/TSM_Mine_Closure_Framework.pdf (accessed 15.11.24).

Maest A.S., Kuipers J.R., Travers C.L., Atkins D.A. (2005): Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art.- p., Butte, MT and Boulder, CO (Kuipers & Associates, Buka Environmental, Stratus Consulting), https://earthworks.org/files/publications/PredictionsReportFinal.pdf (accessed 20.11.24).

Martin Duque, J.F., Tejedor, M., Martin-Moreno, C., Nicolau, J.M., Zapico, I. (2019): Geomorphic rehabilitation in Europe: recognition as best available technology and its role in LIFE projects.- in: Fourie, A.B., Tibbett, M. [Eds.] Mine Closure 2019: Proc. 13th Intern. Conf. on Mine Closure: 133-146, Australian Centre for Geomechanics, Perth, https://doi.org/10.36487/ACG_rep/1915_12_Duque (accessed 09.04.24).

MWEI-BREF Garbarino, E., Orveillon, G., Saveyn, H.G.M., Barthe, P., Eder, P. (2018): Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries in accordance with Directive 2006/21/EC.- JRC Science for Policy Report, EUR 28963 EN: 722 p., http://publications.jrc.ec.europa.eu/repository/handle/JRC109657.

Njambi, R. (2022): Full spectrum: Multispectral imagery and hyperspectral imagery.- up42 blog entry, 16.12.22, https://up42.com/blog/full-spectrum-multispectral-imagery-and-hyperspectral-imagery (accessed 14.11.24).

Ovaskainen, N., Luodes, N., Eerola, T., Marasmi, C., (2024): Sensitivity maps of potential conflicts over natural resources usage. Deliverable 3.2 of the Critical raw materials extraction in environmentally protected areas (CIRAN) project. Grant Agreement No. 101091483 of the European Union's Horizon Europe research and innovation programme: 52 p.

Parbhakar-Fox, A., Baumgartner, R. (2023): Action Versus Reaction: How Geometallurgy Can Improve Mine Waste Management Across the Life-of-Mine.- Elements, **19**(6): 371-376, https://doi.org/10.2138/gselements.19.6.371.

Pilotto, F. et mult. al. (2020): Meta-analysis of multidecadal biodiversity trends in Europe.- Nature Communications, **11**: 3486, https://doi.org/10.1038/s41467-020-17171-y.

Reggiani G., Boitani L., Amori G. (2001): I "contenuti" ecologici di una rete ecologica.- 2001. In: Uomini e Parchi oggi. Reti ecologiche, Quaderni di Gargnano, **4**: 74-83 (Centro Studi V. Giacomini).

Smeets E., Weterings, R. (1999): Environmental indicators: Typology and overview.- EEA Technical report No. 25: 19 p., Copenhagen (European Environment Agency), https://www.eea.europa.eu/publications/TEC25 (accessed 19.09.24).

Tampieri, G. [Ed.] (2010): Perdita della biodiversità, fra antropocentrismo e centralità dell'ecosistema.- Ecoscienza - Rivista di ARPA, Agenzia Regionale Prevenzione e Ambiente dell'Emilia-Romagna, 1(**3**): 140 p., Bologna (ARPA), https://www.arpae.it/it/ecoscienza/numeri-ecoscienza/anno-2010/numero-3-anno-2010/es3_2010_bassa.pdf/@@display-file/file/ES3_2010_bassa.pdf (accessed 16.07.24).

Tost, M., Lesser, P., Poelzer, G., Akhouri, U., Gugerell, K. (2021): Social Licence to Operate (SLO) Guidelines For Europe.- H2020 Project MIREU, Deliverable D4.3: 27 p., https://mireu.eu/sites/default/files/2021-05/D%204.3.pdf (accessed 25.07.24).

UNECE – United Nations Economic Commission for Europe (2015): Bridging Document between the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) Template and the United Nations Framework Classification for Resources (UNFC).- 6 p., https://unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC_specs/Revised_CRIRSCO_Template_UNFC_Bridging_Document.pdf (accessed 19.02.24).

UNECE – United Nations Economic Commission for Europe (2016): Specifications for the application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to Geothermal Energy Resources.- 28 p., https://unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC_GEOTH/UNFC.Geothermal.Specs.pdf (accessed 14.12.22).

UNECE – United Nations Economic Commission for Europe (2017): Guidelines for Application of the United Nations Framework Classifification for Resources (UNFC) to Uranium and Thorium Resources.- UNECE Energy Series, **55**: 64 p., https://unece.org/DAM/energy/images/pub/1734723E_WEB.pdf (accessed 21.10.24).

UNECE – United Nations Economic Commission for Europe (2019): United Nations Resource Management System - An Overview of Concepts, Objectives and Requirements.- ECE Energy Series, 68: 52 p., https://unece.org/sites/default/files/2021-05/2017886_E_ECE_ENERGY_134_WEB.pdf (accessed 19.02.24).

UNECE – United Nations Economic Commission for Europe (2021): Supplementary Specifications for the Application of the United Nations Framework Classification for Resources to Minerals.- 27 p., https://unece.org/sites/default/files/2022-01/UNFC%20Mineral%20Specifications%202021.pdf (accessed 19.02.24).

UNECE – United Nations Economic Commission for Europe (2022a): Supplementary Specifications for the application of the United Nations Framework Classification for Resources (Update 2019) to Geothermal Energy Resources.- 26 p., https://unece.org/sites/default/files/2022-12/UNFC_Geothermal_Specs_25October2022.pdf (accessed 19.02.24).

UNECE – United Nations Economic Commission for Europe (2022b): UNFC Guidance Europe - Guidance for the Application of the United Nations Framework Classification for Resources (UNFC) for Mineral and Anthropogenic Resources in Europe.- 55 p., https://unece.org/sites/default/files/2022-11/UNFC%20GUIDANCE%20EUROPE-FINAL.pdf (accessed 19.02.24).

UNECE – United Nations Economic Commission for Europe (2024): Bridging Document between the Committee for Mineral Reserves International Reporting Standards Template and the United Nations Framework Classification for Resources.- UNECE Report ECE/ENERGY/GE.3/2024/5: 20 p., Geneva, https://unece.org/sites/default/files/2024-04/CRIRSCO_Template_UNFC_BD_ECE_ENERGY_GE.3_2024_5_ENG.pdf (accessed 16.10.24).

VCS Victoria State Government (2020): Preparation of Rehabilitation Plans. Guideline for Mining & Prospecting Projects, February 2020, Version 1.0. Earth Resources Regulation.- 73 p., https://earthresources.vic.gov.au/__data/assets/pdf_file/0018/513342/Preparation-of-rehabilitation-plans-Guideline-for-mining-and-prospecting-projects-February-2020.pdf (accessed 15.11.24).

WB World Bank (n.d.): Mine Closure: A Toolbox for Governments.- 87 p., New York, https://documents1.worldbank.org/curated/en/278831617774355047/pdf/Mine-Closure-A-Toolbox-for-Governments.pdf (accessed 15.11.24).

10 Appendix I – Risk catalogues

10.1 Exploration-related risks

Exploration-related Risks		
Risk Category		**Impact**
Exploration / prospecting personal working in the field	Water	Activities e.g. stream sampling (water, sediment) disturbing aquatic life
	Biological	Disturbance of plant cover and wildlife by human presence
		Disturbance of plant cover and wildlife by mode of transport used (e.g. snow machine, tracked vehicle)
		Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
	Societal	Disquietude and apprehension among locals due stranger(s) in the area
		Disturbance of archaeological or heritage sites
Stream sampling	Water	Turbidity due to stream sediment sampling
		Water contamination through loss of containment of hazardous substances
	Biological	Stream sampling (water, sediment) disturbs aquatic life
		Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
		Injury / loss of life and / or property damage due to lightning strike
Soil sampling	Water	Contamination through uncontrolled loss of hazardous substances
	Soil	Disturbance of soil due to sampling activity
	Biological	Disturbance of plant cover and wildlife by human presence
		Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
		Injury / loss of life and / or property damage due to lightning strike
	Culture	Disturbance of archaeological or heritage sites
Trench sampling	Geotechnical	Slope instability leading to sliding of material
	Soil	Disturbance of plant cover and wildlife by human presence
		Disturbance of soil due to sampling activity
		Disturbance of archaeological or heritage sites
		Soil contamination through uncontrolled loss of hazardous substances
	Air	Incidents involving accumulation of toxic gases in a trench posing a health risk
	Electrical	Incident involving cutting buried electrical lines
	Natural	Flooding of trench in excessive rains
		Lightning strike
Ground geophysics (Ground penetrating Radar (GPR), geomagnetic, and hammer seismic surveys, Vibroseismic trails, Explosive seismics, downhole surveys)	Water	Contamination from spilled drilling fluids
		Loss of oils and hydraulic fluids in the environment
	Soil	Soil compaction by heavy plant (e.g. vibroseis vehicles)
	Biological	Disturbance of plant cover and wildlife due to human presence, heavy vehicles and explosions
	Noise/vibration	Disturbance of public by vibrations and explosions
	Kinetic energy	Unplanned structural damage (e.g. windows)
		Risk related to storage and handling of explosives
	Thermal	Uncontrolled spread of fire caused by geophysical equipment and explosions (e.g. due to inadequate response plan and equipment)
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
		Injury / loss of life and / or property damage due to lightning strike
	Culture	Disturbance of archaeological or heritage sites
	Societal	Disquietude and apprehension among locals due to vibroseis vehicles in the field
		Disquietude and apprehension among locals due to seismic activities

Drilling	Water	Contamination from spilled drilling fluids, chips and slurry
		Loss of oils and hydraulic fluids in the environment
		Short-circuiting and cross-contamination between aquifers due to inadequate lining and sealing between aquifers upon completion
		Penetration of surface contamination into unsealed boreholes
	Soil	Contamination from spilled drilling fluids, chips and slurry
		Soil compaction by heavy plant and drill-pad construction
	Biological	Severe disturbance of plant cover and wild-life due to heavy vehicles and explosions
	Noise/vibration	Disturbance of locals by vibrations and explosions
	Kinetic energy	Explosion due to encounter of flammable gases whilst drilling
		Dropped objects or fall from height
		Release of stored energy (electrical, hydraulic, other stored energy, lifting/pulling devices) leading to personal injury, loss of life and / or property damage
	Thermal	Uncontrolled spread of fire caused by drilling or related activity (e.g. due to inadequate response plan and equipment)
	Radiation	Incident involving downhole survey instrumentation involving nuclear source
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
	Societal	Disquietude and apprehension among locals due to drilling activities
Road Transport	Water	Loss of oils and hydraulic fluids in the environment off-road and during maintenance in the field
	Soil	Environmental contamination due to loss of hazardous materials or samples on the road
	Air	SO_2, NO_x, CO_2, PM_{10} releases from IC engines
	Dust	Dust raised by road vehicles
	Noise/vibration	Noise and vibration from road vehicles
	Kinetic energy	Vehicle collision possibly involving the public
		Vehicle collision with wildlife
	Natural	Vehicle accident due to inadequate road conditions (e.g. snow, wet etc)
		Equipment failure due to exposure to extreme temperature (heat or cold)
	Societal	Vehicle accident with loss of life and/or damage to property
Aircraft / helicopter transport	Water	Uncontrolled loss of hydrocarbons (oils, fuel and hydraulic fluids) in the environment during maintenance in the field
	Soil	Contamination of soil / environment due to aircraft crashes
	Air	SO_2, NO_x, CO_2, PM_{10} releases from IC engines
	Dust	Dust raised by aircraft
	Noise/vibration	Noise from aircraft movements
	Kinetic energy	Aircraft accidents and possibly loss of life
		Collision with wildlife (e.g. birds)
	Thermal	Uncontrolled spread of fire caused by aircraft accident
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
	Societal	Public apprehension due to low-flying aircrafts or drones
Field camp	Water	Water contamination due to uncontrolled loss of contaminants impacting water quality and aquatic life
	Soil	Uncontrolled loss of fluids (e.g. oils, hydraulic fluids, sewate) in the environment from camp facilities and vehicles
		Soil compaction by heavy plant and camp construction
	Thermal	Fire in buildings / structures
		Fire / explosion of electric power generation system
	Natural	Equipment failure due to exposure to extreme temperature (heat or cold)
		Human / wildlife interaction leading to disturbances of wildlife / injury
		Interaction of wildlife on the runway with aircraft leading to accident (e.g. reindeer)
	Infrastructure	Aircraft runway/ landing pad inadequate leading to environmental incident

External / general risks	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
	Culture	Safety and environmental awareness not embedded in culture potentially leading to environmental incidents
	Cyber	Data transfer / loss due to data security breach / theft
	Societal	Loss of land access through landowners due to negative relations
		Negative impact / stoppage of project due to sabotage
		Violent behaviour against field staff

10.2 Planning-related risks

Planning-related Risks		
Risk Category		**Impact**
Strategic planning	Site selection	Location of surface facilities can cause disturbances to the natural environment, wildlife, archaeological or heritage sites or human settlements
		Habitat fragmentation by surface installations and extractive waste management facilities
		Cumulative impacts from several mining and other industrial facilities
		Site planning without potential future requirements in mind (e.g. size of site, locations of EWFs, etc.)
		Resource availability and competition, e.g. water for processing, electric power
		Site inaccessibility (e.g. seasonal access only, mode of transport)
	Nature	Location prone to natural catastrophic events, e.g. extreme temperatures, tornados
	Financial	Market demand and access
		Commodity pricing
		Financial and legal jurisdiction (e.g. impact of royalties, taxes)
	Permitting and licensing	Not obtaining license to operate or mayor delays in construction / project / mine life cycle
	Geohazards	Seismicity
		Flooding
		Landslides
		Karst
Construction planning	Societal	Type of workforce (contractors, unionised etc.) leading to strikes / work delays
		Availability of work force and housing of work force
	Operation	Incidents linked to in the field conducted baseline studies (e.g. environmental and archaeological)
		Equipment compatible and available
Operations planning	Technical	Life of project reduced due to inadequate planning e.g. resource / reserve delineation, mining and processing method, appropriate equipment choices for environment and compatibility
	Cyber	Data transfer / loss due to data security breach / theft
		Inadequate internet access for site requirements
	Operation	Equipment compatible and available
	Labour	Lack of required skills
Waste management planning	Hazardous substances	Leakage of contaminants into the environment / water due inadequate design of liners etc.
	Dust	Dust exposure into environment
	Sustainability	Inadequate separation of waste streams prevents re-use and recycling
	Geotechnical	Tailings dam failure due to inadequate design
Decommissioning planning	Operations	Availability of equipment
		Availability of required work force
		Design of facility makes dismantling hazardous
Closure planning	Operations	Operational issues (e.g. availability of equipment) to complete closure as per requirements
	Structures	Unplanned cave-ins and structural failures
	Regulatory	Changes in laws, requirements for closure and rehabilitation
	Financial	Financial backing unavailable to complete closure as per requirements
Rehabilitation planning	Operations	Rehabilitation not cost and time effective
	Governance	Rehabilitation not successful as per set requirements
		Rehabilitation plans rejected by regulators
	Societal	Rehabilitation plans rejected by local population
Long-term management planning	Societal	Negative impact on environment and local communities
		Negative reputational impact on mining company / project owner
		Long-term management plans rejected by local population
General	Culture	Safety and environmental awareness not embedded in culture potentially leading environmental incidents

10.3 Mine construction-related risks

Mine construction-related Risks		
Risk Category		**Impact**
Site preparation	Water	Water contamination due to loss of oils and hydraulic fluids from site preparation equipment
	Biological	Disruption and displacement of wildlife by clearing operations
		Potential killing of wildlife by clearing operations
	Noise/Vibration	Noise disturbance of public and wildlife due to clearing operations
	Culture	Disturbance of archaeological sites
	Societal	Disturbance of public due to landscape appearance changes
Site construction (including infrastructure outside the mine site)	Geotechnical	Land-slides at temporary earth structures
	Water	Loss of oils and hydraulic fluids from earthmoving plant
		Stream turbidity due to increased erosion
	Soil	Loss of top-soil functionality
	Biological	Disturbance of plant cover and wildlife by earth-moving operations
	Air	Dust generation and off-site dispersal
	Noise	Noise disturbance of public by construction operations
Building construction	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust and fibres on-site and off-site due to moving plant
	Kinetic energy	Dropping hazards (tools and materials form overhead)
		Release of stored energy (electrical, hydraulic, ship lines, lifting/pulling devices)
		Dropped objects
		Loss of life / injury or property damage due to vehicle collision with persons or wildlife
		Structural failure / collapse
		Hoist failure
	Societal	Environmental disturbances (visual pollution)
Shaft sinking and tunnelling, pit excavation	Geotechnical	Fall of ground due to geotechnical instability of freshly excavated shafts and tunnels
		Subsidence due to draw-down of groundwater
	Water	(Cross-)contamination of water-bearing strata
		Groundwater draw-down
		Water contamination due to uncontained loss of oils and hydraulic fluids from equipment
		Water contamination due to uncontained loss of drilling fluids
	Air	Radom-release from mine ventilation to the environment
		SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust generation on-site and off-site due to moving plant
	Noise/vibration	Noise and vibration in-mine
		Noise and vibration off-site
	Kinetic energy	Seismic shock waves from blasting damaging buildings off-site
		Air shock waves from blasting damaging windows etc. off-site
		Underground fire
		Underground explosion
		Unexploded charges in rubble
		Risks associated with explosives storage and handling
		Entanglement / crush of person
		Inrush / flood
	Radiation	Radioactive gases (Radon) – releases with ventilation

Off-site transport between sites	Soil	Lost loads (e.g. hazardous substances) causing contamination of soil
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust contamination e.g. of roads, settlements
	Noise/vibration	Vehicle noise in protected areas and settlements
	Kinetic energy	Vehicle / vehicle collision or vehicle / person collision - involving public
		Rail incident
	Biological	Road accidents involving wildlife
	Societal	Road accidents involving the public
External / general risks	Water	Flooding of mine due to weather conditions
		Land-slides due to weather conditions
		Water contamination due to uncontrolled loss of contaminants (e.g. sewage)
	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
		Permanent or irreversible impact to a common species or ecosystem element
	Kinetic energy	Collapse due to earthquakes (underground, open-cast)
		Explosions of equipment
	Thermal	Equipment failure due to exposure to extreme temperature (heat or cold)
		Inadequate precaution for hot work leading to fires
		Fire in buildings / structures / machinery
	Societal	Negative impact / stoppage of project due to sabotage
		Violent behaviour against field staff by e.g. activists leading to project disruption / stoppage
	Regulatory	Loss of license due to non-/inadequate adherence to permit requirements
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
Extractive waste management		The specific risks are discussed in a separate section

10.4 Mining-related risks

Mining-related Risks		
Risk Category		**Impact**
Underground mining	Geotechnical	Roof falls / fall of ground
		Cave-ins
		Failure of pillars
		Failure of mine props and liners
		Failure of back-fill
		Subsidence due to collapsing mine works
		Air-blast due to collapsing mine openings
	Water	Outbursts
		Underground inrush/flood (mining into an unknown body of water)
		Underground inrush/flood due to failing dams and water-proofing measures
		Failure of drainage systems
		Groundwater draw-down
		Failure of sump water treatment systems
		Acid and other mine drainage discharges
		Contaminated effluents (sump waters)
		Uncontrolled loss of oils and hydraulic fluids from equipment
	Air	Explosive (CH_4), suffocating (CO_2), poisonous (H_2S) gases
		SO_2, NOx, CO_2, PM_{10} releases from IC engines
		Pressure blast (air blast)
	Dust	Dust generation due to vehicle and conveyor belt movement
		Dust explosions
		Dust discharges from mine ventilation off site
		Release of hazardous minerals (asbestos, silica, ...)
	Noise/Vibration	Vibrations off-site from blasting
		Micro-seismic activity due to re-equilibration of the rocks
		Seismic events due to collapsing open mine works and activation of faults
		Ambient noise from ventilation shafts
	Kinetic energy	Seismic shock waves from blasting damaging buildings at surface
		Risks associated with explosives storage and handling
		Unplanned explosion (e.g. unexploded charges, gas, dust, etc.)
	Thermal	Fire hazards (e.g. coal, pyrite, ...)
	Radiation	Radon releases to environment through ventilation
Open-cast mining and quarrying	Geotechnical	Slope slumps
		Hydraulic heave
		Rock face stability / fall of ground
	Water	Acid and other mine drainage discharges
		Contaminated effluents
		Failure of drainage systems
		Failure of drainage and seepage water treatment systems
		Uncontrolled loss of oils and hydraulic fluids from mobile and stationary plant
		Groundwater draw-down
		Inrush of water / flooding
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
		Pressure blast (air blast)
	Dust	Dust dispersal due to vehicle and conveyor belt movement
		Dust dispersal from blasting on-site and off-site
		Dispersal of hazardous minerals (asbestos, silica, ...)

	Noise/Vibration	Noise exposure of the public due to heavy equipment such as haul trucks and conveyer belts
		Vibrations off-site from blasting
	Kinetic energy	Seismic shock waves damaging buildings at surface
		Air shock-waves damaging off-site buildings
		Unplanned explosion (e.g. due to unexploded charges, gas etc.)
Solution mining	Water	Failure of hydraulic protection wells
		Short-circuiting and cross-contamination between aquifers due to inadequate lining and sealing between aquifers upon completion
		Uncontrolled loss of lixiviants or pregnant solutions
		Chemical spills during lixiviant preparation
		Contaminated effluents
		Failure of decant water treatment systems
		Uncontrolled loss of drilling fluids
		Uncontrolled loss of oils and hydraulic fluids in the environment
		Penetration of surface contamination into unsealed boreholes
Trans-shipment between sites	Water	Uncontained loss of fluids e.g. at fuelling station or during road accidents
	Soil	Loss of material from heavy equipment / haul trucks on public roads
		Off-site loss of material from conveyor belts, cable cars etc.
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust in protected areas and settlements
	Noise/vibration	Vehicle noise in protected areas and settlements
	Biological	Road accidents involving wildlife
	Kinetic energy	Road accidents involving lorries
		Accidents during transport of heavy plant
	Societal	Road accidents involving the public
External / general risks	Water	Flooding of mine due to weather conditions
		Landslides due to weather conditions
	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
		Permanent or irreversible impact to a common species or ecosystem element
	Kinetic energy	Collapse of mine structures due to earthquakes
	Culture	Safety and environmental awareness not embedded in culture potentially leading to environmental incidents
	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
	Security	Negative impact / stoppage of project due to sabotage
		Violent behaviour against field staff by e.g. activists leading to project disruption / stoppage
	Cyber	Data or service loss due to data security breach / theft
Extractive waste management		The specific risks are discussed in a separate section

10.5 Processing-related risks

Processing-related Risks		
Risk Category		**Impact**
Trans-shipment of excavated materials and intermediates	Water	Loss of oils and hydraulic fluids from equipment
	Soil	Loss of material from heavy equipment / haul trucks on public roads
		Loss of material from conveyor belts
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
		Loss of containment of hazardous gases
		Loss of containment of hazardous chemicals
	Dust	Dust generation due to vehicle and conveyor belt movement
	Noise/vibration	Noise exposure of the public due to lorries and conveyer belts
	Kinetic energy	Hoist failure
		Road accidents involving wildlife
		Structural failure
		Loss of containment of molten material
	Societal	Road accidents involving the public
Crushing and comminution	Water	Containment loss of oils and hydraulic fluids from equipment
		Loss of containment of hazardous chemicals
	Soil	Containment loss of materials from heavy equipment / haul trucks and loading machinery
		Containment loss of materials from heavy equipment / haul trucks on public roads
		Loss of material from conveyor belts
		Loss of containment of hazardous chemicals
		Failure of silos etc.
	Air	Loss of containment of hazardous gas
	Dust	Dust emissions from crushing and comminution
		Dust generation due to vehicle and conveyor belt movement
		Emissions of hazardous minerals (asbestos, silica, NORM)
	Noise/vibration	Noise exposure of the public due to crushing and comminution machinery
	Kinetic	Dropped objects from height
		Structural failure of installations
Wet processing	Water	Uncontrolled loss of processing fluids
		Uncontrolled loss during processing fluid preparation
		Accidental discharges of untreated processing fluids
		Leakage from leaching pads
		Failure of pipes and tanks
		Failure of decant water treatment systems
		Regional water stress due to extraction of process water
	Air	Olfactory nuisances off-site
	Biological	Biohazards e.g. from bacteria used in advanced processing techniques
	Kinetic energy	Failure of pressurised vessels
		Structural failure
Thermal processing	Water	Uncontrolled loss of processing fluids
		Uncontrolled loss during processing fluid preparation
	Air	Failure of flue-gas scrubbing
		SO_2, NOx, CO_2, PM_{10} releases from processing plants
	Dust	Releases of dust (coarser)
		Release of hazardous minerals (asbestos, silica, ...)
	Thermal	Fire risk in plant
		Loss of containment of molten material
	Kinetic	Structural failure

	Electrical	Electrocution / shock due to damaged/ incorrect electrical installations / hot work in flooded areas
	Radiation	NORM accumulation in stacks and scrubbers
External / general risks	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated" equipment
		Permanent or irreversible impact to a common species or ecosystem element
	Natural hazards	Structural damage to infrastructure/ plant due to seismic events
		Structural damage to infrastructure/ plant due to due to strong rainfalls and flooding
		Production stoppage due to major natural events e.g. major rain fall, tornado, snow
	Culture	Safety and environmental awareness not embedded in culture potentially leading environmental incidents
	Thermal	Inadequate precaution for hot work leading to fire or explosion
	Security	Negative impact / stoppage due to sabotage
		Violent behaviour against staff by e.g. activists
	Cyber	Data or service loss due to data security breach / theft
	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
Extractive waste management		The specific risk are discussed in a separate section

10.6 Transport-related risks

Transport-related Risks		
Risk Category		**Impact**
Rail transport	Water	Surface- and groundwater contamination due to release of Uncontrolled substances
		Loss of oils and hydraulic fluids to the environment
	Soil	Uncontrolled loss of product or by-product from waggons and during loading/unloading or accidents
	Biological	Collision with wildlife
		Fragmentation of ecoystems by railway lines
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust from inadequately covered wagons; loading / unloading activity
		Release of hazardous minerals (asbestos, silica, NORM, ...)
	Noise/vibration	Noise and vibration from shunting and rail traffic
	Kinetic energy	Rail accidents, derailments
		Structural failure of loading / unloading facilities and infrastructure
	Electrical	Electrocution / shock due to contact with overhead catenary
	Societal	Nuisance of continuous railway operation
Road transport	Water	Surface- and groundwater contamination due to release of Uncontrolled substances
		Uncontrolled loss of oils and hydraulic fluids to the environment
	Soil	Uncontrolled loss of product or by-product from haul trucks and during loading/unloading or accidents
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust from inadequately loaded/covered vehicles
		Release of hazardous minerals (asbestos, silica, NORM. ...)
	Noise/vibration	Noise and vibration from road traffic
	Kinetic	Road accidents involving members of the public
		Road accidents involving wildlife
	Societal	Degradation of road system due to use of heavy equipment
		Nuisance of continuous road traffic in settlements
External / general risks	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated vehicles
		Permanent or irreversible impact to ecosystems
	Natural hazards	Structural damage to infrastructure/ mode of transport due to seismic events
		Structural damage to infrastructure/ mode of transport due to due to strong rainfalls and flooding
		Equipment failure due to exposure to extreme temperature (heat or cold)
	Culture	Safety and environmental awareness not embedded in culture potentially leading to environmental incidents
	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
	Cyber	Data or service loss due to data security breach / theft
	Security	Negative impact / stoppage due to sabotage
		Violent behaviour against staff by e.g. activists

10.7 Extractive waste-related risks

Extractive Waste-related Risks		
Risk Category		**Impact**
On-site materials movement	Water	Uncontrolled loss of chemicals due to road accidents with tankers
		Uncontrolled loss of oils and hydraulic fluids from earth-moving plant
		Uncontrolled loss due to failure of tailings pumping systems
	Soil	Uncontrolled loss of material from lorries on public roads
		Uncontrolled loss of material from conveyor belts, cable cars etc.
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust generation due to vehicle and conveyor belt movement
	Noise/vibration	Vehicle noise in protected areas and settlements
	Kinetic energy	Road accidents involving wildlife
		Road accidents involving the public
	Societal	Nuisance of traffic on public roads
Top-soil management	Geotechnical	Slope stability
		Erosion
	Water	Failure of drainage systems
		Surface water turbidity due to erosion
	Biological	Failure of re-revegetation
	Dust	Dust generation from uncovered material
Overburden disposal	Geotechnical	Slope slumps
		Hydraulic heave
		Stability of cover
		Erosion
	Water	Acid and other rock drainage generation
		Failure of drainage systems
		Surface water turbidity due to erosion
		Groundwater / surface water contamination
	Biological	Failure of re-revegetation
	Dust	Dust generation from uncovered material
		Release of hazardous minerals (asbestos, silica, NORM, ...)
Below-grade material and gangue disposal	Geotechnical	Slope slumps
		Hydraulic heave
		Stability of cover
		Erosion
		Personal /equipment inundation (especially on live stockpiles)
	Water	Acid and other rock drainage generation
		Contaminant dispersal by surface run-off
		Failure of drainage and diversion systems
		Failure of drainage and seepage water treatment systems
		Surface water turbidity due to erosion
		Groundwater / surface water contamination
	Biological	Failure of re-revegetation
	Dust	Dust generation from uncovered material
		Release of hazardous minerals (asbestos, silica, NORM, ...)
	Thermal	Self-ignition of organic materials (oil shale)
	Radiation	Radon releases

Tailings management facilities	Geotechnical	Dam stability / tailings dam failure
		Hydraulic heave at toe
		Environmental damage and injury / loss of life due to dam failure
		Slumping slopes
		Internal erosion (suffusion, piping)
		Retrograde dam erosion due to overtopping of decant water
		Catastrophic release of tailings due to slope slumps (‘tsunami’)
		Failure of cover (e.g. hydraulic heave)
		Erosion (general)
		Geotechnical instabilities due to permafrost thawing
	Water	Failure of drainage and diversion systems
		Failure of bottom liners or the impermeable natural soil basal layer
		Overtopping of dams
		Acid and other rock drainage generation
		Contaminant dispersal by overtopping
		Failure of drainage and seepage water treatment systems
		Surface water turbidity due to erosion
		Groundwater / surface water contamination
	Biological	Failure of re-revegetation
	Dust	Dust generation from uncovered tailings
		Release of hazardous minerals (asbestos, silica, NORM, ...)
	Radiation	Radon releases
External/ general risks	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment or materials
		Permanent or irreversible impact to ecosystems
	Natural hazards	Slope/dam collapse due to seismic events
		Collapse/land-slides due to strong rainfalls and flooding
		Flooding of site due to weather conditions
	Culture	Safety and environmental awareness not embedded in culture potentially leading to environmental incidents
	Security	Negative impact / stoppage due to sabotage
		Violent behaviour against staff by e.g. activists
	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Third party (e.g. contractor, JV) related risks with regard to impact on public / government relations / license to operate

10.8 Decommissioning and closure-related risks

Decommissioning and closure-related Risks		
Risk Category		**Impact**
Abandoned sites	Geotechnical	Instability due to lack of maintenance of open mine works
		Instability due to lack of maintenance of slopes
		Instability due to lack of maintenance of dams - tailings dam failure
		Instability due to lack of maintenance of covers
	Water	ARD in surface and groundwaters
		Turbidity in surface due to unmaintained covers
	Dust	Dust generation due to unmaintained covers and unsuccessful revegetation
	Radiation	Radon release due to failing covers
	Societal	Failure of access prevention (collapse/sabotage of fences)
		Falls into uncovered shafts / sinkholes
		Uncontrolled access to hazardous substances including explosives
Decommissioning	Water	Release of hazardous substances during demolition and dismantling
		Uncontrolled loss of oils and hydraulic fluids to groundwaters
	Soil	Uncontrolled loss of oils and hydraulic fluids to the environment
		Uncontrolled loss of hazardous materials from structures being dismantled
	Biological	Disturbance of wildlife due to demolition activities
	Dust	Off-site dust from demolition activities
		Release of hazardous minerals (asbestos, silica, NORM, ...)
		Dust generation from e.g. crushing of concrete
	Noise/Vibration	Off-site noise and vibration due to demolition and dismantling activities
	Kinetic energy	Collateral damage from demolitions (incl. blasting)
		Collateral damage from collapsing buildings during demolitions
	Societal	Nuisance of demolition activities
Closure	Geotechnical	Instability of dams, slopes, rock faces etc. during the transition phase
		Instability of slopes in open-pit mines during flooding
	Water	Turbidity in surface waters due to erosion during the transition phase
		AMD generation due to flooding mine voids
		Release of contaminants into surrounding aquifers due to AMD
		Leaching of explosives residues and other contaminants during flooding
		Short-circuiting between aquifers due to rising water levels
	Dust	Dust releases before covers and re-vegetation becomes effective
Trans-shipment between sites	Water	Uncontrolled loss of chemicals due to road accidents
	Soil	Loss of material from heavy equipment / lorries on public roads
		Off-site loss of material from conveyor belts, cable cars etc.
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust in protected areas and settlements
	Noise/vibration	Vehicle noise off-site
	Kinetic energy	Road accidents involving wildlife
		Accidents during transport of heavy plant
		Road accidents involving the public
		Accidents during off-site removal of materials for recycling or re-use
	Thermal	Overheated vehicles causing wild-fires
	Societal	Nuisance of transport activities

External / general risks	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment
		Permanent or irreversible impact to ecosystems
	Natural hazards	Structural damage to infrastructure due to seismic events
		Structural damage to infrastructure due to due to strong rainfalls and flooding
	Regulatory	Loss of license to operate due to non-adherence or inadequate adherence to permit requirements
		Failure to proceed to closure due to lack of regulatory approval
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
	Security	Negative impact / stoppage due to sabotage
		Violent behaviour against staff by e.g. activists

10.9 Rehabilitation-related risks

Rehabilitation-related Risks		
Risk Category		**Impact**
Underground mines	Geotechnical	Long-term stability of open mine workings
		Long-term stability of coffer dams and back-fill
	Water	Acid and other mine drainage generation
		Release of contaminants into surrounding aquifers due to AMD
		Short-circuiting between aquifers following flooding
		Disturbance of regional hydrology due to draw-down reequilibration
		Starvation of rivers due to stoppage of mine-water discharges
		Failure of decant mine water treatment systems
	Air	CH_4, CO_2, H_2S or radon exhalation from open mine workings
		SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Noise/vibration	Micro-seismic activity due to re-equilibration of the rocks
	Societal	Fall into unsealed shafts
		Unauthorised entry into rehabilitated mine workings
Open-cast mines	Geotechnical	Long-term stability of slopes and rock-faces
		Slope instability due to rising water levels
	Water	Acid and other mine drainage generation releasing contaminants into surrounding aquifers
		Disturbance of regional hydrology due to draw-down re-equilibrating
		Starvation of rivers due to stoppage of mine-water discharges
		Failure of decant mine water treatment systems
	Air	SO_2, NO_x, CO_2, PM_{10} releases from IC engines
	Dust	Dust dispersal due to vehicle movement
		Dispersal of hazardous minerals (asbestos, silica, NORM, ...)
	Noise/vibration	Noise exposure of the public due to rehabilitation works
Solution mines	Water	Residual lixiviants that cannot be removed by pump-and-treat
		Short-circuiting between aquifers
		Failure of hydraulic protection wells
		Uncontrolled loss of lixiviants or residual pregnant solutions
		Uncontrolled loss of chemicals during lixiviant removal
		Contaminated effluents
		Failure of decant water treatment systems
		Uncontrolled loss of oils and hydraulic fluids in the environment
		Penetration of surface contamination into unsealed boreholes
Waste rock dumps	Geotechnical	Long-term stability of slopes
		Erosion of covers
		Long-term frost resistance of covers
		Long-term functioning of covers
		Loss of stability of covers due to bioturbation (burrowing animals, plant roots, etc.)
	Water	Acid and other rock drainage generation
		Failure of surface water diversions
		Failure of toe drainage
		Release of contaminants into the aqueous environment
		Turbidity in surface waters due to eroded material
	Soil	Contamination due to dispersion of eroded material
	Biological	Failure of re-vegetation efforts
	Air	CH_4 or radon leakage into buildings developed on site or into the surrounding environment
		SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust due to eroding covers and uncovered waste

		Dust dispersal due to vehicle movement
		Dispersal of hazardous minerals (asbestos, silica, NORM, ...)
	Societal	Human intrusion (e.g. extraction of aggregates)
		Unsuitable re-development (e.g. foundations in covers)
Tailings management facilities	Geotechnical	Long-term stability of dams
		Hydraulic heave at dam toe
		Retrograde dam erosion due to overtopping
		Failure of caps due to uneven tailings dewatering
		Erosion of caps
		Long-term frost resistance of covers
		Long-term functioning of covers
		Loss of stability of covers due to bioturbation (burrowing animals, plant roots, etc.)
	Water	Acid and other rock drainage generation
		Failure of liners
		Failure/silting up of surface water diversions
		Failure of toe drainage
		Seepage due to failure of liners
		Release of contaminants into the aqueous environment
		Turbidity is surface waters due to erosion
	Biological	Failure of re-vegetation efforts
	Air	Radon leakage into buildings developed on site or into the surrounding environment
		SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust due to eroding covers and uncovered dried tailings
		Dust dispersal due to vehicle movement
		Dispersal of hazardous minerals (asbestos, silica, NROM, ...)
	Societal	Human intrusion (e.g. extraction of aggregate)
		Unsuitable re-development (e.g. foundations in covers)
Trans-shipment between sites	Water	Uncontrolled loss of hazardous substances
	Soil	Loss of material from heavy equipment / lorries on public roads
	Air	SO_2, NOx, CO_2, PM_{10} releases from IC engines
	Dust	Dust in protected area and settlements
	Noise/vibration	Vehicle noise off-site
	Kinetic	Road accidents involving wildlife
		Road accidents involving the public
		Accidents during off-site removal of materials for recycling or re-use
		Accidents during transport of heavy plant
	Societal	Nuisance of transport activities
External / general risks	Biological	Introduction of foreign species into local fauna/ flora through e.g. contaminated equipment or materials
		Permanent or irreversible impact to ecosystems element
	Natural	Collapses due to earthquakes (slopes and dams)
		Collapse/ landslides due to strong rainfalls, flooding, winds, snow
		Changing climatic boundary conditions (e.g. amount and intensity of precipitation)
	Regulatory	Failure to proceed to rehabilitation due to lack of regulatory approval
	Societal	Safety and environmental awareness not embedded in culture potentially leading to environmental incidents
		Third party (e.g. contractor) related risks with regard to impact on public / government relations / license to operate
	Finance	Stoppage of rehabilitation due to unavailability of funding
	Security	Negative impact / stoppage due to sabotage
		Violent behaviour against staff by e.g. activists