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Application of the United Nations Framework Classification for Resources and the United Nations Resource Management System in different geographical contexts

United Nations Framework Classification for Resources Case Study – Base Metal Tailings Storage Facility Bollrich, Germany

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Summary

In pioneering case studies, the United Nations Framework Classification for Resources (UNFC) has been applied successfully to anthropogenic raw materials such as municipal waste, incineration residues, electronic waste and base metal tailings. These case studies deal with identified raw materials recovery projects, partially with advanced degrees of maturity. Currently, case studies are missing which demonstrate the progression of project development from their identification to their first on-site exploration. Such case studies are necessary to determine the relevant factors for the promotion of anthropogenic raw materials recovery projects. In this case study, two consecutive approaches are presented which provide guidance on how to assess and classify base metal tailings mining projects with different degrees of maturity under consideration of all dimensions of sustainability. The approaches are applied to the base metal tailings storage facility Bollrich (Germany). It contains 7.2 million tonnes of tailings, including critical raw materials and other economically highly important metals. The following conclusions can be drawn from the case study: (i) the inclusion of project benefits and risks at local level in project classification is important due to the frequent proximity to human settlements; (ii) a sustainable assessment of raw materials recovery projects requires the consideration of all raw materials, including potentially harmful contents and their impacts; and (iii) a transparent presentation of sustainability aspects can help market actors to better evaluate the risks related to an investment. In general, applying UNFC helps to create an inventory of all base metals contained in tailing storage facilities, as well as to identify project potentials and barriers. Lastly, it supports decision-making for the further development of projects.

* The rescheduled session dates will be confirmed at a later stage.

Contents

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Author Contributions

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- Rudolf Suppes: conceptualisation, writing – original draft preparation
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Executive Summary

In pioneering case studies, the United Nations Framework Classification for Resources (UNFC) has been applied successfully to anthropogenic raw materials such as municipal waste, incineration residues, electronic waste and base metal tailings. These case studies deal with identified raw materials recovery projects, partially with advanced degrees of maturity. Currently, case studies are missing which demonstrate the progression of project development from their identification to their first on-site exploration. Such case studies are necessary to determine the relevant factors for the promotion of anthropogenic raw materials recovery projects.

In this article, two consecutive approaches are presented which provide guidance on how to assess and classify base metal tailings mining projects with different degrees of maturity under consideration of all dimensions of sustainability. Step (1): the assessment is performed with a systematic desk-based screening. It is based on publicly accessible data to achieve a preliminary result. The aim is to quickly identify a potential raw materials recovery project. Step (2): the assessment is performed with the help of on-site exploration data. It is performed for the overall project and for subprojects for the recovery of individual raw materials with the aim of evaluating the impact of different project scenarios. For the sake of transparency, the rating results for economic, environmental, social, and legal aspects are differentiated; and they are summarised in a heat map-like categorisation matrix.

The approaches are applied to the case study base metal tailings storage facility Bollrich (Germany), which was part of the Rammelsberg mining operation. It contains 7.1 million tonnes (Mt) of tailings and it was chosen since it contains Critical Raw Materials (barite ($BaSO_4$), cobalt (Co), gallium (Ga) and indium (In)) and other economically highly important metals (copper (Cu), lead (Pb), and zinc (Zn)). Additionally, it is situated in a complex environment with many stakeholders in the vicinity, and the necessity to act due to environmental and social risks. As on-site exploration data from preceding research projects is available, the developed procedure can be tested for its applicability.

In Step (1), a ‘Prospective Project’ (E3F3G4) is identified, and its further exploration is recommended. In Step (2), three scenarios are evaluated: rehabilitation (NRR0), recovery with a focus on economic (CRR1) and sustainability aspects (ERR2). The net present values of NRR0, CRR1 and ERR2 are EUR −124.5 mio., EUR 73.9 mio. and EUR 172.5 mio., respectively. The recoverable quantities are 2.7 Mt (CRR1) and 7.1 Mt (ERR2). Ultimately, the overall project for all three scenarios is rated E3.3F3G3. The assessment shows that the project’s main drivers are (a) environmental rehabilitation, (b) economic viability, and (c) the long-term positive development of a region facing economic and environmental issues. Key barriers to the further development are (d) the conduction of a detailed stakeholder assessment, (e) the proposal of mitigating measures for environmental impacts, (f) the preparation of legal permit applications, (g) metallurgical testing of material from the upper part of the tailings storage facility, (h) the development of a solution for the disposal of the neutralised sludge from the Rammelsberg mine during/after project execution, and (i) a detailed raw materials estimate.

The following conclusions can be drawn from the presented case study: (i) the inclusion of project benefits and risks at local level in project classification is important due to the frequent proximity to human settlements; (ii) a sustainable assessment of raw materials recovery projects requires the consideration of all raw materials, including potentially harmful contents and their impacts; and (iii) a transparent presentation of sustainability aspects can help market actors to better evaluate the risks related to an investment. In general, the UNFC-compliant assessment and classification approach helps to create an inventory of all base metals contained in tailings storage facilities, and to identify project potentials and barriers. Lastly, it supports decision-making for the further development of projects.

I. Introduction

1. The global demand for mineral raw materials has been increasing steadily for decades [1-3].[1] With the resulting increased production of mineral raw materials, the production of mine waste is also increasing, estimated to be as high as 25 Gt per annum [4]. A large part of the mine waste produced during ore processing occurs in the form finely ground rock, left over after separating the target fraction from the unwanted fraction, so-called tailings. Tailings can have severe impacts on the environment and human health [5]. The impacts are generally expected to increase in the future due to an increased risk related to extreme weather occurrences as a result of climate change [6].

2. Many industrialised countries and regions such as the European Union (EU) are highly dependent on raw material imports. The associated supply risks, especially for Critical Raw Materials (CRMs) [7,8], result in a high interest in recovering raw materials from anthropogenic sources such as base metal tailings.

3. A review of 66 case study reports on the recovery of raw materials from mine wastes and metallurgical wastes shows that the main target group (80%) are market actors such as investors or mining companies [9]. Factors such as environmental impact or market acceptance are usually not taken into account [9]. Socio-political acceptance is addressed in only three case studies [9]. The review demonstrates that a raw materials recovery project assessment which considers all dimensions of sustainability is currently an exception.

4. However, a paradigm shift is currently taking place and policymakers are increasingly demanding sustainable sourcing of raw materials to address public concerns [3,7]. In addition, the financial sector has recognised that investments can be jeopardised if techno-economic aspects only are focused, and environmental and social aspects are neglected [3]. The transparent communication of project sustainability is a challenge since different stakeholders perceive the objectives differently [10]. A notable example is the case study on raw materials recovery from mineral waste in the Harz region (Germany) in reference [11]. The case study shows that, due to the regional historical and societal context, stakeholders can have different attitudes on similar projects that are located close to each other. These range from approval to rejection. The application of the United Nations Framework Classification for Resources (UNFC) principles provides the opportunity to make the Sustainable Development Goals (SDGs) for responsible production and consumption as well as for climate action a vital part of raw materials classification.

5. An approach is required which provides a transparent overview of the information gathered to create a basis for a factual discussion with all stakeholders. This enables incorporation of all their needs into the way forward to achieve the set objectives. This can generate trust between mining companies, investors and the public.

6. It is demonstrated in this article how UNFC can be applied in practice to base metal tailings mining projects with different degrees of maturity with the aim of identifying potentially sustainable raw materials recovery projects in two steps. It is based on the studies by Suppes and Heuss-Aßbichler [12-14] who first applied UNFC to base metal tailings in a systematic manner under consideration of all dimensions of sustainability. In the beginning of Step (1), the potential of a base metal tailings deposit has not yet been investigated. A pre-selection for further investigation is made with a desk-based screening to identify a potentially viable project. Step (2) requires initial on-site exploration data. Based on the assessment results, follow-up actions can be suggested which are required to promote a project from an economic, environmental, social and legal perspective.

7. The tailings deposit Bollrich was selected for the case study since it contains CRMs (barite ($BaSO_4$), cobalt (Co), gallium (Ga) and indium (In)) and other economically highly important metals (copper (Cu), lead (Pb), and zinc (Zn)). [15]. Additionally, it is situated in a complex environment with many stakeholders in the vicinity, with the need to respond to environmental and social risks [13]. As on-site exploration data from other research projects (REWITA [15] amongst others) are available, they can be used as an example for the

[1] Numbers in square brackets refer to references in the bibliography.

implementation of the developed approach. The conceptualisation of the case study presented in this article began in mid-2020 and the database was last updated in early 2021.

II. Methods

A. UNFC Context

8. The current UNFC concept and the specifications for its application to anthropogenic raw materials, in which relevant terminology and principles are defined, can be found in references [16] and [17], respectively.

9. In UNFC, projects are classified based on three fundamental criteria: environmental-socio-economic viability (E-axis), technical feasibility (F-axis), and degree of confidence in the estimate (G-axis).

10. In pioneering case studies, UNFC has successfully been applied to anthropogenic raw materials such as municipal waste [18], municipal waste incineration residues [19,20], electronic waste [18,21] and base metal tailings [12]. The existing case studies on anthropogenic raw materials deal with identified raw materials recovery projects, partially with advanced degrees of maturity.

11. Currently, case studies are missing which demonstrate the progression of project development from their identification to their first on-site exploration. Such case studies are necessary to discover the potential of a project and to identify the relevant factors for the promotion of anthropogenic raw materials recovery projects.

B. Step (1). Desk-Based Exploration: Screening Study

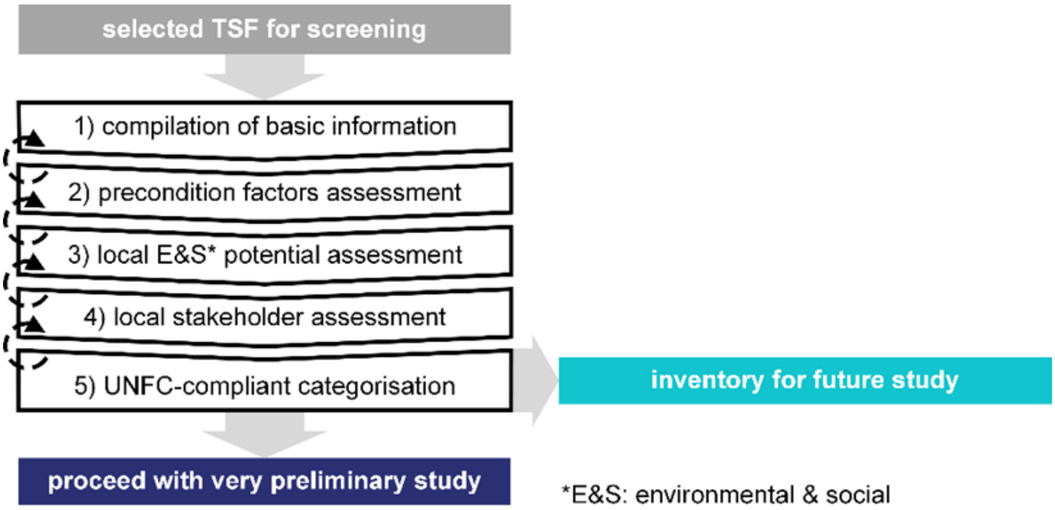
12. The desk-based screening is intended to be the first step in project development where a potential raw material deposit has not yet been investigated, similar to reconnaissance exploration of natural mineral raw materials. It aims at a quick identification of project potentials and barriers [13]. The approach builds on a desk-based data collection from publicly accessible internet sources, satellite images, scientific databases and thematic geoscientific maps.

13. The screening is performed in five stages of increasing effort to obtain information (cf., Figure I). Based on the results at each stage, the investigation can be terminated prematurely before too much time and money are invested. Similarly, if necessary, each assessment stage can be reiterated to obtain further information or when new information becomes available. The assessment criteria for each stage, including geological, technological, economic, environmental, social and legal aspects, are described in reference [13].

14. The five assessment stages are [13]: (1) collection of basic information such as location, environment, contained raw materials, the condition the tailings storage facility is in, and potential safety risks; (2) assessment of defined preconditions regarding economic, environmental and/or social aspects which justify an interest in a tailings storage facility; (3) assessment of local environmental and social benefits which can be generated from removing a tailings storage facility; (4) assessment of stakeholders directly affected by a tailings storage facility or its removal; (5) consolidation of the collected knowledge for UNFC-compliant categorisation, which is the basis for making recommendations on how to proceed further with the case study.

Figure I

Step (1). Five stages for a systematic tailings storage facility (TSF) screening compliant with UNFC



Note: The dotted lines indicate possible iterative steps.
Source: Adapted from reference [13].

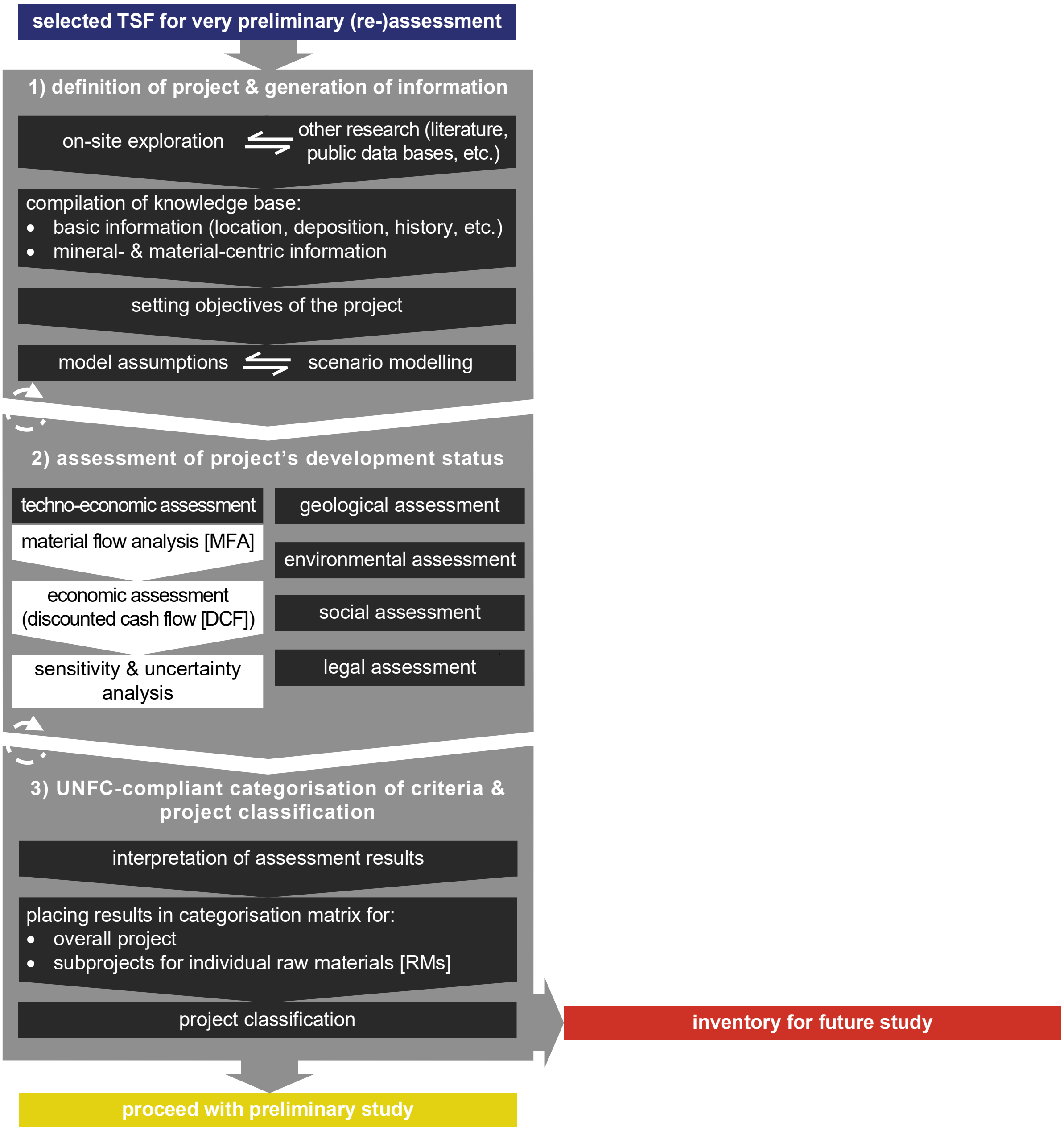
C. Step (2). On-Site Exploration: Very Preliminary Study

15. The second step involves the assessment of the very preliminary project. It is based on already generated on-site exploration data, which provides an initial estimate of a project's viability. The assessment is performed in three stages (cf., Figure II): (1) definition of a project and generation of information, (2) assessment of project development status, and (3) UNFC-compliant categorisation of criteria and project classification [14].

16. The third stage is performed using a UNFC-compliant categorisation matrix (cf., reference [14] for details). Factors with high uncertainty remain in the 3rd UNFC Sub-categorisation (3.1, 3.2, 3.3) while more developed factors can be rated higher in the UNFC's main Categories (1, 2, 3). This matrix distinguishes between the overall project and subprojects for individual raw materials. For the sake of transparency, the rating results for the E-axis are differentiated into economic (econ.), environmental (env.), social (soc.), and legal (leg.) aspects. After a literature review and critical analysis of established assessment factors from primary mining, literature on sustainability in mining, and case studies, 44 factors were identified, adapted and modified.

Figure II

Step (2). Three stages for a systematic assessment and classification



Note: Three stages for a systematic assessment and classification of raw materials recovery from tailings storage facilities (TSF) at very preliminary level based on on-site exploration data.

Source: Adapted after reference [14].

III. Case Study

A. General Information on the Tailings Storage Facility Bollrich

17. The tailings storage facility Bollrich (Germany) was part of the Rammelsberg mining operation in which mainly gold (Au), silver (Ag), Pb, Cu and Zn were produced [22]. An overview of the area around the tailings storage facility and a close-up are given in Figure III and Figure IV, respectively. Additional geographic information is given in Table 1.

18. The tailings storage facility was abandoned in 1988 after around 50 years of operation [15]. It contains the CRMs $BaSO_4$, Co, Ga and In, and the economically highly important

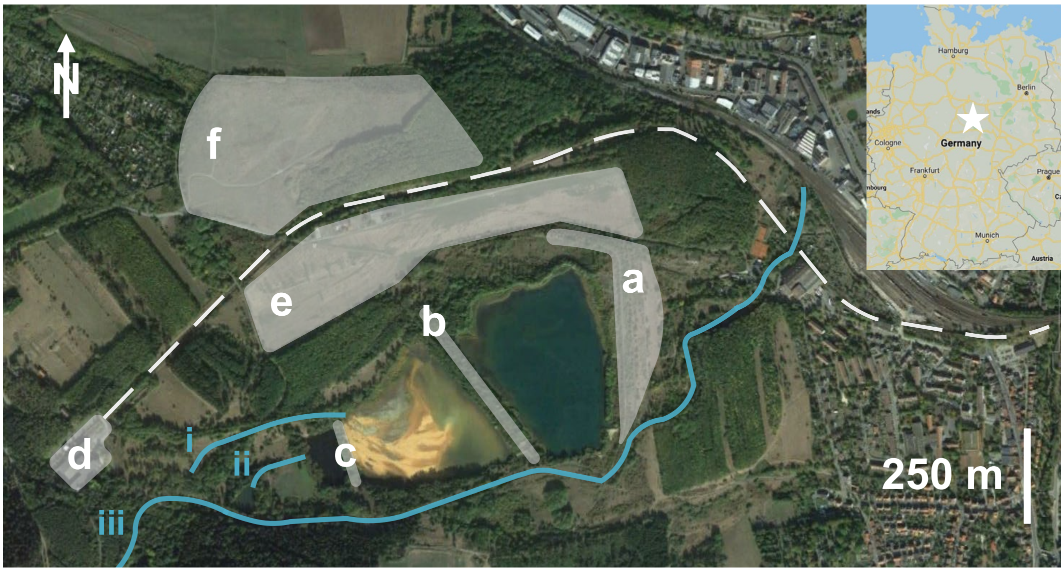
elements Cu, Pb and Zn [15,23]. The deposit is one of the rare potential CRM sources in Germany [24].

Figure III
Location of the tailings storage facility Bollrich, the associated disused processing plant and public infrastructure

Note: The associated disused processing plant is shown in the light shaded areas, bottom left pictures. The white lines represent public railway tracks, the red line represents the disused railway to the Bollrich processing plant, the yellow lines represent country roads, the orange line represents a section of the four-lane federal highway B6, and the blue line represents the motorway A395.

Source: Adapted after Google Earth [25] and adapted from reference [13].

Figure IV
Close-up of the near environment of the tailings storage facility Bollrich



Note: (a) marks the main dam, (b) the middle dam, (c) the water retention dam, (d) the disused processing plant, (e) a glider airfield, and (f) the disused landfill Paradiesgrund. The neutralised sludge between the dams (b, c) is yellowish. The white dotted line marks the disused railway connection from Oker to the processing plant, (i) the stream of neutralised mine water, (ii) the connection between the pond Gelmketeich and the water retention pond, and (iii) the river Gelmke.

Source: Adapted after Google Earth [25] and adapted from reference [14].

19. The tailings deposit was first explored in the 1980s with a focus on geological aspects and a main interest in base metals and barite [26]. In addition to qualitative aspects, such as

contained minerals and deposition, quantitative aspects, such as raw material quantities and grain size distributions, were investigated. The investigation also includes the neutralised sludge in the deposit, its contents, the distribution of minerals and its volume.

20. In the 2010s, the tailings deposit was explored in a large research project (REWITA) by Goldmann et al. [15]. The focus was mainly set on geology and technical feasibility of raw materials recovery to determine the project's viability. The investigation includes the consideration of the exploration results from reference [26] and historical production data for validation. Preliminary stakeholder interviews were also performed [11]. However, environmental, social and legal aspects were not taken into account as potential project driving factors.

Table 1
Geographic information about the tailings storage facility Bollrich's environment

Category & Factor	*Data*	*Sources*
(1) Location	Goslar district (Germany) (51°54'8.97"N, 10°27'47.31"E)	[25]
(2) Topography	At the foot of the Harz Mountain range, up to 1,141 m altitude	[27]
(3) Local Geology	Folded & faulted Paleozoic rocks of the Harz Mountains are uplifted & thrust over younger Mesozoic rocks of the Harz foreland along the Northern Harz Boundary fault leading to steeply tilting & partly inverted Mesozoic strata, Mesozoic rocks are largely composed of Triassic to Cretaceous sedimentary rocks of varying composition (i.e., mostly impure limestones, clastic sandstones [greywackes] & shales), younger Quaternary sediments are rare & locally limited	[28]
(4) Climate	Moderately warm (−0.7 to 16.3°C (average 7.2°C)), rain precipitation 911 mm/a	[29,30]

Source: Adapted from reference [14].

B. Results

1. Step (1). Desk-Based Exploration: Screening Study

21. The screening study is performed in the five stages explained in section II (subsection B). The goal is to determine whether the tailings storage facility Bollrich is suitable for further investigation at all, including on-site exploration. The study is based on publicly accessible data at this step.

22. The assessment is premised on the assumption that the potential for tailings mining has not yet been investigated. Therefore, all scientific studies, media reports, and on-site exploration results [e.g., 11,15,26,31] are excluded in this step. The sources of information for the screening study are limited to the combination of observations on Google Earth [32], a Google search which evolved from the observations, scientific publications, non-scientific public data published on websites or in reports for instance.

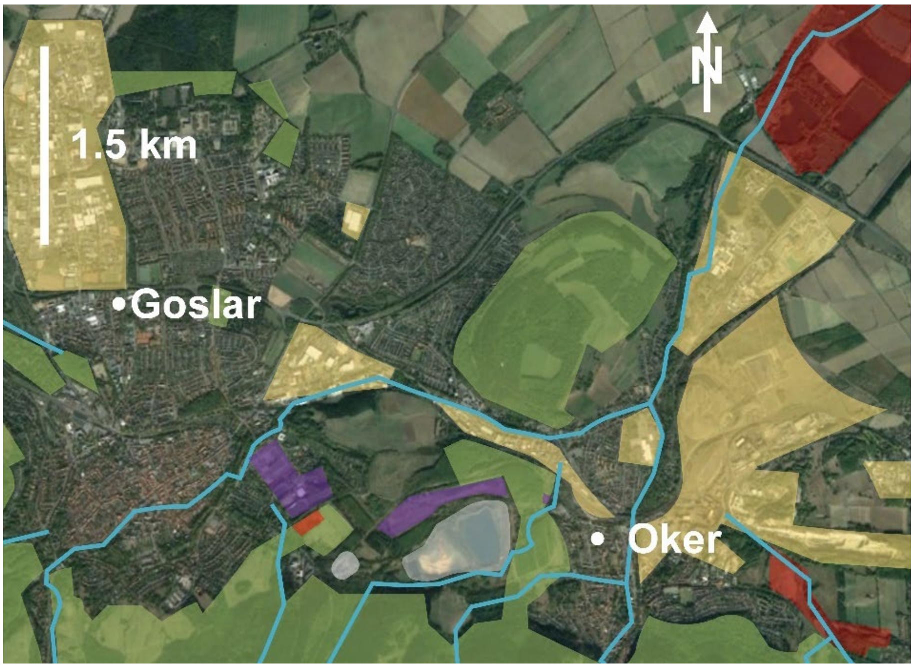
23. The screening is carried out within a radius of 10 km around the tailings storage facility, with special focus on the area downstream of the tailings storage facility. It is assumed that this area would be immediately affected by a tailings storage facility failure [33].

24. In the first assessment stage, most of the required data on the tailings storage facility's content, structure and location could be obtained. However, data on raw material quantities and qualities is missing. Hence, the raw materials content is assumed based on literature on mined ores and their processing [22,34]. In addition, information on the tailings storage facility's geomechanical stability is missing. Overall, it is considered that the continuation of the assessment can be justified with the obtained data.

25. In the second assessment stage, the defined preconditions are assessed. It shows that the tailings storage facility can be economically interesting due to its size, and the presumable content of the CRMs $BaSO_4$ and In, as well as the economically highly relevant raw materials Ag, Au, Cu, Pb and Zn. The presence of buildings, transportation and utility infrastructure in the near vicinity can lower the development costs. The high placement of Germany in the 'Ease of Doing Business' ranking (22 out of 190) [35][2] gives rise to the assumption that favourable regulatory conditions for investment are present.

26. The assessment of environmental and social aspects in the third assessment stage reveals that the conditions in the vicinity of the tailings storage facility are challenging. As shown in Figure V the tailings storage facility is located in vicinity to agricultural, forest, industrial and commercial, nature and water protection, recreation, and residential areas. Therefore, the potential for social conflicts has to be taken into account. Because a failure of the tailings storage facility poses a threat to the environment, its removal could be regarded as an improvement compared to the status quo in this respect.

Figure V
Simplified schematic illustration of the environment around the tailings storage facility Bollrich



Note: The light grey shaded area marks the tailings storage facility Bollrich (right area) and the disused processing plant (left area), the green shaded areas mark protected landscape areas, the red shaded areas mark nature conservation areas, the yellow shaded areas mark industrial and commercial areas, and the purple shaded areas mark sports areas close to the tailings storage facility. The blue lines represent rivers.

Source: Adapted after District of Goslar Environmental Service [36] and Google Earth [25], and adapted from reference [13].

27. In the fourth assessment stage, a group of at least eighteen diverse and socially active stakeholders could be identified. Amongst others, they include environmental Non-Governmental Organisations (NGOs), the Development Association Cultural Heritage Ore Mine Rammelsberg, and the Air Sports Community Goslar.

[2] The ranking was discontinued in 2021 due to accusations of manipulation (https://www.worldbank.org/en/news/statement/2021/09/16/world-bank-group-to-discontinue-doing-business-report, accessed on 01 March 2022). To be consistent with the publications this article is based on, this assessment factor was kept. It is advised to seek an alternative assessment factor which allows for obtaining a quick overview of investment conditions.

28. In the fifth assessment stage, the project is classified as a ‘Prospective Project’ with the categorisation E3F3G4.

29. In sum, the following potentials are identified: it is assumed that (1) the tailings quantity is sufficiently large for a viable recovery, (2) that CRMs and economically highly important metals are present, (3) that the environmental and social risks at status quo are high, (4) that there is high land use-related social tension at status quo, and (5) that favourable investment and infrastructure conditions are present.

30. The following barriers are identified: (1) there is little geological and geotechnical knowledge about the tailings storage facility, and (2) the identified stakeholders might potentially reject the project.

31. Overall, it is recommended to further investigate the tailings storage facility Bollrich through an on-site study to overcome the identified barriers to its classification as a very preliminary project. This includes the consideration of the local stakeholders’ environmental, social and economic interests.

2. Step (2). On-Site Exploration: Very Preliminary Study

32. The very preliminary study is carried out in the three stages as described in section II (subsection C). At this point, results of on-site investigations of the tailings deposit Bollrich are already available. The exploration results are documented in scientific studies [11,15,26,37].

33. The goal of the very preliminary study is to assess and classify the tailings mining project in a structured and UNFC-compliant manner concerning its possible implementation. The results should be presented transparently so that sustainability aspects can be easily identified. As in the previous assessment, this assessment includes an area within a 10 km radius around the tailings storage facility.

34. The first assessment stage includes the project definition and the generation of information. The on-site exploration data and other data are compiled in a knowledge base (cf., Table 2).

35. The on-site exploration activities detailed in references [15,26] include relevant geological, mineralogical and geographic data on plans and section, e.g., sample intervals, grain size distribution, 3D models of the deposit, a concise description of the raw materials calculation, and the analysis of historical records. This data is not shown in this article, with the exception of the drillhole sample points in Figure VI, since the focus is on the exemplary test application of the developed UNFC-compliant approach. However, the data is publicly available [15,26].

36. Three scenarios are conceptualised to highlight the difference between various alternatives ranging from (a) rehabilitation, over (b) conventional raw materials recovery, to (c) sustainable raw materials recovery [14]:

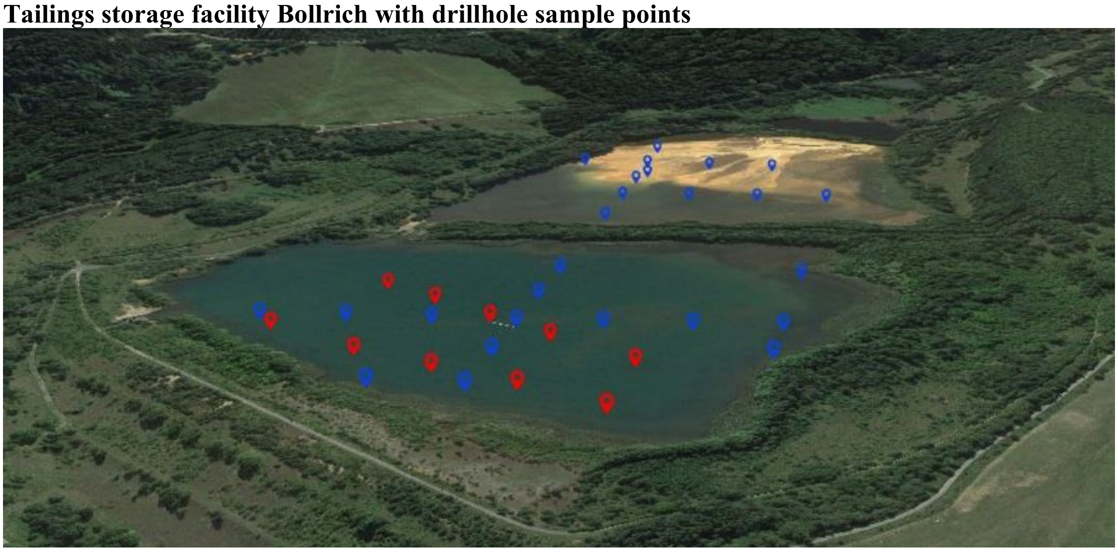
(a) No raw materials recovery (NRR0) – the goal is to create a physically and chemically stable, maintenance-free waste repository, while retaining the current landform. For instance, this can be achieved by installing a leachate collection system, stabilising the tailings storage facility by in-situ concrete injection, sealing its surface, and capturing and treating leachates on site during a 5-year closure phase. During a 30-year aftercare phase, emissions and the tailings storage facility’s stability have to be monitored. For a rough economic estimate, benchmark data from reference [38] is used. The benefits of scenario NRR0 include the minimisation of environmental and social risks by preventing either a dam failure; or the release of contaminants which might occur during raw materials recovery, processing and the transportation of the hazardous tailings in a vulnerable region;

(b) Conventional raw materials recovery (CRR1) – the goal is to recover the most viable raw materials and to rehabilitate the environment. This can be achieved by applying conventional technologies with off-site residue disposal. The tailings are mined in a dredging operation and are processed on site in the existing processing plant at a constant rate during a 10-year period. The processing plant represents the system boundaries and corresponds to the reference point. During a 1-year rehabilitation period, the original landform is restored;

(c) Enhanced raw materials recovery (ERR2) – the goal is to create the highest possible degree of raw material efficiency. For this purpose, the same processes as in CRR1 are applied. In addition, the sales of the mixed residues to a local recycling company for a use in construction materials is also considered.

37. Published data and model assumptions for unavailable data (cf., Table 3) are used to quantitatively assess the material flows and economic viability. They include the assessment of mineralogical properties, such as the composition and chemical alteration; the assessment of technological feasibility, for instance by laboratory-scale mineral processing experiments and conceptual mine planning; and environmental on-site inspections of flora and fauna. The data base for the techno-economic assessment such as capital expenditure (CAPEX) and operating expenditure (OPEX) is given in reference [14].

Figure VI
Tailings storage facility Bollrich with drillhole sample points



Note: Red and blue dots mark the drillholes from the REWITA research project [15] and the research conducted by Woltemate [26], respectively.
Source: Adapted from reference [15].

38. In CRR1 and ERR2, geotechnical and mine planning considerations are conceptual, i.e., no detailed planning has been carried out. A homogeneous deposit is assumed. A conservative estimate is achieved by adapting the low mineral contents from reference [15] (cf., Table 2). Tailings, commodity and residue masses are estimated as dry matter. The amount and composition of generated commodities and residues are evaluated with a material flow analysis (MFA) according to reference [39]. It is based on the multi-stage froth flotation specified in reference [37] (cf., Table 2) for tailings sampled in the lower pond [15]. Material flow uncertainties are neglected.

39. Mine site preparation and rehabilitation costs are considered. In general, the presence of real estate, transportation and utilities infrastructure reduces the mine development costs. Assets and machinery are liquidated at the operation's end at a residual value of 10%. Energy consumption is considered for tailings recovery and processing. A price forecast for mineral concentrates, elements, diesel and electric energy is performed with an autoregressive function applied to historical price data (cf., reference [14]). Chalcopyrite ($CuFeS_2$), galena (PbS) and sphalerite (ZnS) concentrate prices are estimated after reference [40] with a backwards calculation of the Net Smelter Return (NSR). Prices for selling and costs for disposing of residues are fixed due to a lack of data.

Table 2
Excerpt from the knowledge base on the Bollrich tailings deposit to define the project

Category & Factor	*Data*	*Sources*	*UNFC Axis*[a]
(A) Basic Information			
(a) Geogenic Deposit			
(i) Mineralisation	Two strongly deformed lense-shaped main ore bodies (high & low grade), sedimentary exhalative deposit, fine grained (10-30 µm) principle sulphide minerals sphalerite [$(Zn,Fe)S$] & pyrite [FeS_2], less amounts of galena [PbS] & chalcopyrite [$CuFeS_2$], Ag, Au, (average estimated grades 14 wt% Zn, 6 wt% Pb, 2 wt% Cu, 140 g/t Ag & 1 g/t Au), baryte [$BaSO_4$] (average grade 20 wt%), ca. 30 trace elements as Co, Ga & In, hosted by Middle Devonian Wissenbach shales	[25,27,34]	
(b) Tailings Deposit			
(i) Recoverability			
• Quantity & Quality	$V_{tailings}$ = 2,030,000 m³, m_{dry} = 7,100,000 t, ρ = 3.5 t/m³ (weighted mean value), $\rho_{neutralised\ sludge}$ = 2.3 t/m³	[15,26]	G
	Exploration of the deposit: (i) 10 drill cores (17-28 m) taken in the upper pond along main dam & parallel to main dam in the middle of the pond, analysis of 16 elements; (ii) 90 water depth metering points	[15]	G
	26 drill cores, analysis of 4 elements & 3 minerals	[26]	
• Safety Considerations	Dam stability: occurrence of a sinkhole at the northern part of the tailings storage facility documented in 1986 & several sinkholes near the tailings storage facility reported in the past which are associated with karstified geological structures nearby; expertise from 1986 concludes that the tailings storage facility is not imminently threatened; confirmed by current calculations; unexploded ordnance: the existence of WWII ordnance cannot be excluded[b]	[15]	F
(ii) Rehabilitation	Not rehabilitated, ecological succession, no signs of AMD or erosion observable[c]	[15], observed on Google Earth [25]	
(iii) Assessment Status			
• Maturity Level	Very preliminary study	-	
• Characterisation	Complete for the lower pond	[15]	
	Partial for the upper pond; not all elements/minerals analysed; amount, composition & shape of deposition of mine water neutralised sludge roughly estimated		
• Evaluation	Partial	-	
• Classification	UNFC classification as Prospective Project (E3F3G4) based on screening study	[13]	
(iv) Social Impacts			
• Health Protection	No apparent imminent hazards known, negative impacts through dermal contact, ingestion or inhalation not given; risk assessment not performed	[15]	E (soc.)
• SLO[d]	Positive perception of project idea by administration, environ. NGOs & scientists	[11]	E (soc.)
	Local population's perception of project idea unknown	-	
(v) Environmental Impacts			
• Pollution	Possible negative impacts unknown; disused landfill 'Paradiesgrund' located 250 m N; possible influence of tailings mining on landfill needs to be investigated	[15]	E (env.)
	Tailings storage facility's base not sealed & in direct contact with tailings		

Table 2 *Continued*

Category & Factor	*Data*			*Sources*	*UNFC Axis*[a]
• Landscape	Integrated into the landscape (visible from up close or from hills), environment adapted through natural succession, gilder airfield ~100 m N, hiking trails nearby			cf., Figure IV	E (env.)
• Current Status	On-site inspection identified protected flora, & aerial & soil fauna			[15]	E (env.)
• Protected Areas	Conservation areas & protected landscapes nearby			[15]	E (env.)
• Secondary Use	Since 1966 neutralised mine water has been discharged			[26]	E (env.)
(c) Technology					
(i) Mine Planning	Mine planning considerations on a conceptual basis (dredging)			-	F
(ii) Processing	Extraction of $BaSO_4$, Co, Cu, Ga, In, Pb, Zn, & inert residues evaluated in discontinuous laboratory experiments on tailings from the lower pond; processing sequences: (i) sulphide separation together with contaminants (rougher+cleaner+leaching), (ii) $BaSO_4$ separation rougher+cleaner+ scavenger+conditioning); recovery rates (tested on material from lower pond; ammonia leaching route for sulphides): $BaSO_4$ (74%), Co (12%), Cu (74%), Ga (2%), In (26%), Pb (65%), Zn (72%), & inert material (93%); processing tests on tailings from the upper pond not performed; precipitation of SO_4 ions in multiple stages necessary to recover metals			[37]	F
(d) Legislation / Licensing					
(i) Ownership	Bergbau Goslar GmbH (address: Bergtal 18, 38640 Goslar)			[15]	E (leg.)
(ii) Legal Framework	Currently supervised under the German Federal Mining Act (BBergG)			[15]	E (leg.)
(B) Mineral- & Material-Centric Information					
(a) Chemical & Mineralogical Composition					
(i) Elements	Ba (14.4), Cu (0.15), Fe (12.5), Pb (1.2), Zn (1.3) [mean, wt%]; As (700), Cd (30), Co (185), Ga (23), In (5.9), Tl (70) [mean, µg/g]			[15]	G
(ii) Minerals					G
• Quantities:	Estimated minerals content [total dry mass / share of tailings' mass]			[15]	
• $BaSO_4$	1,739,000 t	/	24.5 wt% (monomineralic)		
• $CuFeS_2$	31,000 t	/	0.44 wt%		
• FeS_2	1,086,000 t	/	15.3 wt% (7.1 wt% Fe in tailings)		
• PbS	85,000 t	/	1.2 wt%		
• ZnS	149,000 t	/	2.1 wt%		
• Wissenbach shales	2,350,000 t	/	33.1 wt%		
• ankerite	1,611,000 t	/	22.7 wt%		
• neutralised sludge:	mass unknown; high & low Zn & $BaSO_4$ concentration, respectively			[26]	
(b) Physicochemical Properties					
• Particle Size Distribution	Tailings: very fine, 90% of particles <60 µm, predominantly 2-60 µm, based on analysis from 4 samples, neutralised sludge: very fine, ~80% of particles <20 µm			[15,26]	G
• Geomechanical Properties	Classified into geomechanical category GK III (DIN 1054): highly difficult regarding the interaction of structure & subsoil			[41]	G

Note: The dark grey shaded boxes indicate data associated with high uncertainties, the light grey shaded boxes indicate data associated with moderate uncertainties and the dashes indicate factors for which no information is available.

Source: Adapted from reference [14].

[a] env.: environmental aspects, soc.: social aspects, leg.: legal aspects.

[b] WWII: Word War II.

[c] AMD: Acid mine drainage.

[d] SLO: Social license to operate.

Table 3
Summary of model assumptions for the case study tailings storage facility Bollrich

Model Assumption
(1) For in-situ rehabilitation, the tailings storage facility abandonment is performed as for DK II class landfills[a] under the German Landfill Regulation (DepV) [42].
(2) Mass of dam material is neglected in mineral raw materials recovery scenarios alongside its further treatment.
(3) Freight costs for commodities & residues to downstream processes are neglected.
(4) All equipment can be used over the whole Life of Mine (LOM) without renewal except for the pipelines & pumps, which are exchanged in year six of the mining operation due to abrasive wear.
(5) Processing plant Bollrich: assets can be used (for operation, administration, etc.), processing machinery can be reactivated & the $BaSO_4$ concentrate can be conditioned on site; basic infrastructure is in place.
(6) Experimental tailings recovery rates from lower pond applicable to tailings from the upper pond, neglecting the influence of neutralised sludge on processing.
(7) No losses & dilution of tailings occur during mining & transport.
(8) The processing plant produces three types of products: (i) a pure industrial mineral concentrate ($BaSO_4$), (ii) a mixed sulphide concentrate ($CuFeS_2$, PbS, ZnS) including all high-technology metals (Co, Ga, In) & heavy metals (As, Cd, Tl), & (iii) mixed residues due to inefficiencies in mineral processing.
(9) There is a market for all produced commodities. Its location and transport costs to the market are not considered.
(10) Smelters pay for the recoverable Co, Ga & In content in the mixed sulphide concentrate based on a recovery with ammonia leaching as specified in reference [37]. A mechanical separation is not possible due to the strong intergrowth of the sulphides.
(11) There is a potential buyer for the mixed residues which are sold at a price of EUR 5 per tonne.
(12) A discount rate of 15% is chosen to reflect a high-risk investment [43].

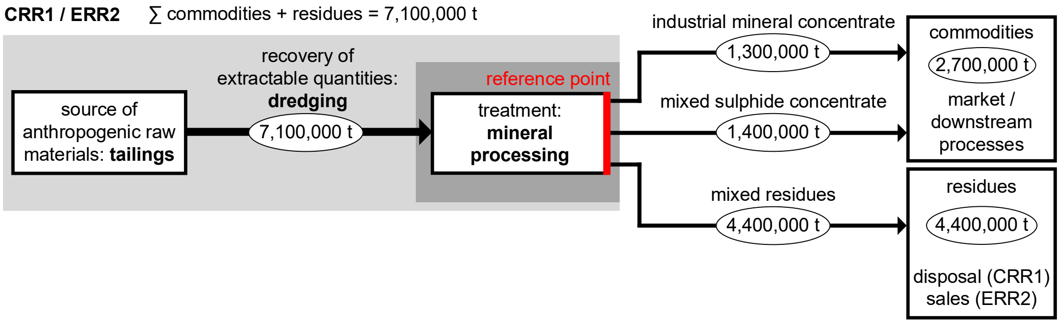
Source: Adapted from reference [14].
[a] Above-ground landfill for contaminated but non-hazardous waste such as pre-treated domestic waste or commercial mineral waste. Geological base and surface sealing are required.

40. In the second assessment stage of the very preliminary study, the project's development status is investigated on the basis of geological, techno-economic, environmental, social, and legal assessments. It is based on the assessment of mineralogical properties, such as the composition and chemical alteration; the assessment of technological feasibility, e.g., by laboratory-scale mineral processing experiments and conceptual mine planning, and environmental on-site inspections of flora and fauna [15].

41. Geological assessment (cf., Table 2): the deposit has been modelled based on direct data on 10 drill cores from the lower pond, and pre-processed historical data on 14 and 12 drill cores from lower and upper pond, respectively. Both ponds contain a mixture of tailings and neutralised sludge [26]. The model was validated with historical production data [15]. Detailed mineralogical and processing investigations, including metallurgical raw materials recovery, were performed for the technical feasibility of the project. It showed that, amongst others, the CRMs usually occur as by-products in sulphide (Ag, Au, In, Co, Sb, Ga) and silicate minerals (Ga), while Ba is concentrated in barite ($BaSO_4$). Lastly, there is a knowledge gap on the quantity of the neutralised sludge and possibly other dumped material.

42. A simplified material flow analysis was used for the techno-economic assessment of CRR1 and ERR2 (cf., Figure VII). In total, 7.1 Mt of tailings are mined and processed over 10 years. The commodities leave the system boundaries for off-site conditioning. In CRR1, 2.7 Mt of commodities (i.e., 38 wt% of total tailings) and 4.4 Mt of mixed mineral residues are produced. The commodities consist of an industrial mineral and a mixed sulphide concentrate. In ERR2, all tailings are fully utilised.

Figure VII
Material flow systems and 10-year material flows for the mineral raw materials recovery scenarios (CRR1, ERR2)



Note: The light grey and dark grey shaded fields illustrate the spatial and mineral processing system boundaries, respectively. All figures are rounded to the sixth digit.
Source: Adapted from reference [14].

43. Techno-economic assessment (discounted cash flow (DCF) analysis):

(a) The expected net present values (NPVs) of NRR0, CRR1 and ERR2 are EUR −124.5 million, EUR 73.9 million and EUR 172.5 million, respectively. The NPV in CRR1 becomes negative if a pessimistic price trend is assumed while the NPV in ERR2 is positive regardless of the price forecast;

(b) 98% of all costs in the rehabilitation scenario (NRR0) are attributed to the 5-year closure and leachate phase. Residue disposal is the highest cost factor in CRR1 with a share of 62% of total costs. The OPEX is the second-highest cost factor in CRR1 (excluding residue disposal) and the highest in ERR2 with a share of total costs of 21% and 58%, respectively;

(c) In the raw materials recovery scenarios CRR1 and ERR2, the CRM $BaSO_4$ contributes to 49% and 47% of the revenues, respectively, and it has a share of the total commodity masses of 64.4 wt% and 24.5 wt%, respectively. The second-highest revenues are attributed to Zn with a contribution of 27% and 25%, respectively. ZnS has a share of the total commodity masses of 5.5 wt% and 2.1 wt%, respectively. The lowest contribution to the revenues (<2%) is attributed to the CRMs Co, Ga and In. The sales of residues contribute 5% to the revenues in ERR2.

44. Environmental assessment based on the status quo risks:

(a) The area around the tailings storage facility is contaminated with heavy metals such as As, Cd, and Pb, which partially exceed the concentration threshold values for soil in parks and recreational areas in Germany [44,45]. No data is available on the tailings storage facility's impact on human health, local flora and fauna, and surface water and groundwater, as no monitoring is currently taking place [15]. However, the unsealed tailings storage facility base represents a risk for the release of contaminants [15];

(b) The main dam can be assumed to be stable with respect to extreme rainfalls in its current state as confirmed by conservative calculations [46]. In the vicinity to the tailings storage facility, karstified zones and the formation of two sinkholes have been reported [15]. In this respect, the long-term risk for the stability of the tailings storage facility is currently unknown.

45. Social assessment addressing the stakeholders of the project including the population in the region:

(a) The Harz region is facing the challenges of demographic change, young people's emigration, a weak economy, and environmental burdens from former mining [11,47]. A particularity is the Goslar community's and city administration's strong awareness of the region's mining history, which is regarded as a cultural heritage and an important factor for tourism [11,47];

(b) An interviewing campaign was conducted by Bleicher et al. [11] to identify the attitude of different stakeholders towards raw materials recovery. The results are the following: generally, raw materials recovery from mine waste is regarded as a development opportunity for the Harz region, and the trust in scientists and the industry is shared by public media. Scientific institutions and the industry are identified as the current regional drivers of CRMs recovery from mine waste. The majority of interviewed stakeholders were in favour of developing knowledge and technologies for mine waste valorisation, and environmental NGOs see raw materials recovery from mine waste as an opportunity to at least partially rehabilitate the environment. The city's administration sees an opportunity to attract highly skilled workers and to strengthen the region's role in the development of novel recycling technologies.

46. Legal assessment based on basic considerations for project implementation:

(a) In general, applications for legal permits need to be drafted;

(b) It needs to be determined whether the mining law and/or waste legislation applies for granting of a mining license/permit [48];

(c) A high degree of effort is likely to be required to obtain environmental permit since preliminary on-site inspections have shown that high-quality flora and fauna ecosystems are present [15]. Therefore, an environmental impact study and a concept for the protection of the ecosystems and/or the remediation of impacts are expected to be necessary. Potential impacts on the surrounding protected natural areas and landscapes need to be assessed.

47. In the third assessment stage, a UNFC-compliant categorisation is performed and the project is classified with the help of a heat map-like categorisation matrix developed in reference [14]. Generally, the lowest rating in a Category is chosen for the rating of the overall Category (cf., reference [49] (p. 37)). The rating results are summarised in the categorisation matrix in Table 4 and Table 5 (cf., reference [14] for the justification for the rating). As no raw materials are recovered in the rehabilitation scenario (NRR0), only the overall project is rated.

48. In sum, all three scenarios have the same categorisation E3.3F3G3 in the overall rating. There is currently no specific Class for this categorisation [cf., reference 16]. In comparison to the categorisation of E3F3G4 in the preceding screening study (cf., subsection III B 1), the G Category could be improved to G3 and the E Categorisation could be specified as E3.3. The scenarios differ in their economic performance, with NRR0 primarily incurring rehabilitation costs, and CRR1 having a higher uncertainty compared to ERR2.

49. The heat map-like presentation in Table 4 and Table 5 enables quick recognition of the project potentials and barriers of the three scenarios. They are discussed in detail below.

50. For the overall project, the following potentials exist according to the current state of project assessment: for all three scenarios, the geological knowledge has a low level of confidence (G3). It is assumed that the conducted sampling and testing suffice to confirm geological and grade continuity between the points of observation. This conclusion is based on the report by Goldmann et el. [15] in which it is recommended to continue with the project, based on their profound geological and mineralogical investigations. Note that there are high uncertainties regarding the neutralised sludge in the upper pond due to the addition of material since the last drill cores were taken in the 1980s.

51. For all scenarios, the infrastructural conditions (F1-F2) and rehabilitation planning (F2) are rated high, except for mining & processing. The scenarios raw materials recovery CRR1 and ERR2 are distinguished by less water consumption (F1).

52. The raw material recovery projects can be expected to be economically viable (E2 econ.). The negative NPV in the pessimistic forecast for CRR1 must be considered but cannot be acknowledged with the current UNFC rating. ERR2 is more resilient in this respect due to the sales of the new residues. The driving revenue factor is the $BaSO_4$ sales due to its relatively high grade (24.5 wt%), the high recovery rate (74%), the high price compared to the other commodities and the forecasted price increase. CRR1 is relatively insensitive to

$BaSO_4$ price variations as the NPV becomes negative when the $BaSO_4$ price decreases by 69%. ERR2 is more resilient as the NPV decreases to 38% when the $BaSO_4$ price drops to EUR 0.

53. As for the social aspects, the retained landscape is rated positively (E2 soc.) since there is no perceivable change for the local residents. In the raw material recovery scenarios (CRR1, ERR2), raw materials recovery has a higher rating regarding social aspects as compared to rehabilitation only in NRR0. In ERR2, the complete tailings valorisation and the degree of raw materials recovery are rated high (E1 soc.).

54. In contrast, the following aspects currently constitute barriers to project development: in CRR1 and ERR1, there are high uncertainties regarding the upper pond with respect to geological knowledge about the neutralised sludge. For the rehabilitation scenario (NRR0), the state of technological development has a low overall rating (F3) due to the uncertainty regarding the presence of World War II ordnance, the conceptual operational design, the unclarified usability of tailings storage facility water and the unclarified long-term storage safety. Metallurgical test work on the tailings from the upper pond is missing (F3) and it is unknown if the neutralised sludge could be valorised in ERR2. These tailings might be difficult to process due to the high sulphate ion content [26]. If they need to be disposed of too, the disposal costs would increase in both scenarios (CRR1, ERR2).

55. The economics of NRR0 are rated low (E3.3 econ.) as only costs are incurred and as there currently is no knowledge about a potential financial support. The environmental aspects are rated low (E3.3 env.) due to the unclarified potential dust emission and in-situ cementation of reactive material. In CRR1 and ERR2, planning considerations such as the resettlement of rare flora and fauna still require fundamental work (E3 env.). In CRR1, the raw materials efficiency (E3.3 soc.) could be improved, as well as the preservation of the raw materials potential in the new residues for future generations (E3.2 soc.). The development status of social aspects is generally low, just as for legal aspects (E3.3 leg.).

56. In general, several factors pose an economic risk to CRR1 and ERR2: residue disposal is the greatest cost factor in CRR1 with 64% of all costs. It is also the greatest economic risk as a price increase of 93% leads to a negative NPV. For instance, a price increase is possible if a further conditioning is necessary to meet the criteria of disposal sites. The economic rating for CRR1 is low (E3.3 econ.) due to the higher uncertainty in the pessimistic price forecast. Regarding CAPEX and OPEX, CRR1 and ERR2 are relatively insensitive to cost variations and they are regarded as economically viable given that the estimates are within the accuracy and contingency range for scoping studies of 50% and 30%, respectively [50].

57. For the subprojects for the recovery of individual raw materials, the state of development for economic and environmental aspects varies significantly: most raw materials have a high economic importance or are CRMs in the EU. All raw materials except for FeS_2 and the inert materials have a clear demand. According to the price forecast based on historical data up to March 2021, the prices for $BaSO_4$, Co and In are expected to rise (E3.1 econ.), to be stagnant for Pb and Zn (E3.2 econ.), and to decrease for Cu and Ga (E3.3 econ.). For the new residues, the Pb solid matter content and dissolved Pb in leachate impede the disposal as inert waste (DK 0 class) (E3.2 env.) [42].

58. There is a clear distinction in the state of development with respect to technological aspects: F2 for $BaSO_4$, F2 for base metals, F1 for FeS_2, F1 for the inert material, and F3 for the CRMs Co, Ga and In. On the extreme ends, Ga and FeS_2 have the lowest (E3.3F3G3) and highest (E3.2F1G3) total ratings, respectively.

59. In CRR1 and ERR1, there are very high uncertainties regarding the upper pond with respect to geological knowledge about the Co, Ca and In contents (G4) as they are assumed based on indirect data.

Table 4
Categorisation matrix for the overall project rating of the rehabilitation scenario (NRR0) and the mineral raw materials recovery scenarios (CRR1, ERR2)

Factor	*Scenario*		
	NRR0	*CRR1*	*ERR2*
	UNFC G Category		
Geological conditions (relevant for project development)			
(1) Quantity	G3	G3	G3
(2) Quality	G3	G3	G3
(3) Homogeneity	G3	G3	G3
	UNFC F Category		
Tailings storage facility condition & risks (relevant for project development)			
(4) Ordnance	F3	F3	F3
Mine planning considerations (relevant for project execution)			
(5) Mine/operational design	F3	F3	F3
(6) Metallurgical test work	-	F3	F3
(7) Water consumption	F3	F1	F1
Infrastructure (relevant for project development)			
(8) Real estate	F1	F1	F1
(9) Mining & processing	-	F3	F3
(10) Utilities	F2	F2	F2
(11) Transportation & access	F2	F2	F2
Post-mining state (relevant for future impacts)			
(12) Residue storage safety	F3	F3	F3
(13) Rehabilitation	F2	F2	F2
	UNFC E Category[a]		
Microeconomic aspects (relevant for project development)			
(14) Economic viability	E3.3	E2	E2
(15) Economic uncertainty	-	E3.3	E3.1
Financial aspects (relevant for project development)			
(16) Investment conditions	-	E3.1	E3.1
(17) Financial support	E3.3	E3.1	E3.1
Environmental impacts during project execution			
(18) Air emissions	E3.3	E3.1	E3.1
(19) Liquid effluent emissions	E3.1	E3.1	E3.1
(20) Noise emissions	E3.2	E3.2	E3.2
Environmental impacts after project execution			
(21) Biodiversity	E3	E3	E3
(22) Land use	E3.2	E3.2	E3.2
(23) Material reactivity	E3.3	E3.1	E3.1
Social impacts during project execution			
(24) Local community	E3.3	E3.2	E3.2
(25) Health & safety	E3.3	E3.3	E3.3
(26) Human rights & business ethics	E3.3	E3.3	E3.3
Social impacts due to project execution			
(27) Wealth distribution	E3.3	E3.3	E3.3
(28) Investment in local human capital	E3.3	E3.3	E3.3
(29) Degree of raw materials recovery	E3.3	E3.2	E1
(30) Raw material valorisation	E3	E3	E1
Social impacts after project execution			
(31) Aftercare	E3	E1	E1
(32) Landscape	E2	E1	E1
Legal situation (relevant for project development)			
(33) Right of mining	E3.3	E3.3	E3.3
(34) Environmental protection	E3.3	E3.3	E3.3
(35) Water protection	E3.3	E3.3	E3.3

Table 4 *Continued*

Factor		*Scenario* NRR0	CRR1	ERR2
		UNFC G Category		
Total Rating[a]		G3	G3	G3
		F3	F3	F3
	econ.	E3.3	E3.3	E3.1
	env.	E3.3	E3.2	E3.2
	soc.	E3.3	E3.3	E3.3
	leg.	E3.3	E3.3	E3.3

Note: For better legibility, each rating result is assigned its own colour ranging from purple for Category 3, including an intense red to pink for the Sub-categories 3.3 to 3.1, orange for Category 2, and green for Category 1.

Source: Adapted from reference [14].

[a] econ.: economic aspects, env.: environmental aspects, soc.: social aspects, leg.: legal aspects.

Table 5

Categorisation matrix for the subproject rating for individual raw materials (CRR1, ERR2)

Factor		*Subprojects for Individual Raw Materials* $BaSO_4$	*Cu*	*Pb*	*Zn*	*Co*	*Ga*	*In*	FeS_2	*inert material*[a]
UNFC G Category										
Geological conditions (relevant for project development)										
(36) Quantity		G3	G3	G3	G3	G3	G3	G3	G3	G3
(37) Quality		G3	G3	G3	G3	G3	G3	G3	G3	G3
(38) Homogeneity		G3	G3	G3	G3	G3	G3	G3	G3	G3
UNFC F Category										
Mine planning considerations (relevant for project execution)										
(39) Recoverability		F2	F2	F2	F2	F3	F3	F3	F1	F1
UNFC E Category[b]										
Microeconomic aspects (relevant for project development)										
(40) Demand		E3.1	E3.1	E3.1	E3.1	E3.1	E3.1	E3.1	E3.2	E3.3
(41) Raw material criticality		E1	E2	E2	E2	E1	E1	E1	E2	E3
(42) Price development		E3.1	E3.3	E3.2	E3.2	E3.1	E3.3	E3.1	-	-
Impacts after project execution										
(43) Solid matter		-	E3.1	E3.2	E3.1	-	-	-	-	E1
(44) Eluate		E3.1	E3.1	E3.2	E3.1	-	-	-	-	E1
Total Rating[b]		G2	G2	G2	G2	G3	G3	G3	G2	G2
		F2	F2	F2	F2	F3	F3	F3	F1	F1
	econ.	E3.1	E3.3	E3.2	E3.2	E3.1	E3.3	E3.1	E3.2	E3.3
	env.	E3.1	E3.1	E3.2	E3.1	-	-	-	-	E1b

Source: Adapted from reference [14].

[a] Wissenbach shales & ankerite.

[b] econ.: economic aspects, env.: environmental aspects.

3. Recommendations: Path Forward for the Case Study

60. The following recommendations are made to achieve a higher rating of the overall project as a ‘Potentially Viable Project’ (E2F2G2) (cf., reference [16]), [14]:

(a) For the economic aspects of the E Category, the determination of site-specific processing costs is necessary since reference values are used in this article. An economic estimation after taxes and other governmental charges is required to make it comparable across country borders [51]. The costs for residue disposal (CRR1) and conditioning for an application in construction materials (ERR2) need to be investigated. The price forecasts need to be updated with current data. In addition, the aspects discussed below also have an economic impact which needs to be considered;

(b) For the environmental aspects of the E Category, the extent of karstified zones needs to be investigated to better assess the risk of a potential damage to the tailings storage facility. The present flora and fauna need to be inventoried in detail; measures for the mitigation of environmental impacts need to be proposed; and rehabilitation, environmental monitoring and post-closure land use plans need to be conceptualised;

(c) For the social aspects of the E Category, a comprehensive systematic stakeholder assessment is required. The process should be transparent and structured to enable a fact-based discussion at all times. Generally, the tailings storage facility’s long-term risks need to be weighed against the temporary disturbance of local nature and communities, potential long-term regional benefits such as environmental rehabilitation, and the local recruitment of the workforce;

(d) For the legal aspects of the E Category, it is necessary, for instance, to estimate and the duration of removing legal barriers, to engage authorities and to prepare permit applications. For the endorsement of a project plan, a disposal site for residues needs to be determined alongside a transportation concept;

(e) For the F Category, technical guidelines such as CEN/TR 16376 might be generally applied to provide guidance on waste characterisation. It should be investigated if the existing processing plant and technology can be reused. The valorisability of the neutralised sludge needs to be investigated. Furthermore, a solution is required for the discharge of the Rammelsberg mine water, preferably with a recovery of raw materials such as Zn. Raw materials efficiency can be increased by valorising the FeS_2 in the tailings and by recovering the high-technology metals As, Cd, Cr, Ni and Tl. All of these elements are required in high-technology applications such as robotics or decarbonised energy production [52]. It should be investigated whether all residues in ERR2 can be valorised sustainably. For instance, the inert material must not contain hazardous elements. A strong pollution of the drainage and process water can be expected during mining for which a solution needs to be found;

(f) For the G Category, a higher rating as G2 requires the data base for and results of the geostatistical assessment of the raw materials to be presented in a transparent way which enables an evaluation of the quality of the work performed. In addition, a cut-off grade needs to be determined. Furthermore, the amount of dam material needs to be investigated. An uncertainty analysis of all contained masses in the tailings deposit could help to consider errors in the geological estimates. The amount, composition, and distribution of neutralised sludge need to be investigated, especially for the upper pond.

IV. Conclusions

61. A reliable supply of raw materials is essential for the prosperity of societies, industrial production and modern living standards [9,53]. However, the mining industry is facing strong scepticism from communities, partly due to a previous track record of negative environmental and social impacts, accompanied by poor communication with community stakeholders [3,54]. Consequently, mining companies and financial market actors are increasingly recognising non-economic factors as potential barriers to the development of raw materials recovery projects [3].

62. A major concern of communities affected by raw materials recovery is sustainability, i.e., not only an economically viable, but also an environmentally and socially acceptable recovery [54]. Meeting these requirements is, amongst others, the goal of the UN SDGs [7]. The implication for the mining industry is that sustainability needs to be considered from the beginning of project development. This can be achieved by establishing a raw materials classification which considers environmental and social aspects as essential as economic ones. The assessment and classification of raw materials under UNFC can make this possible [7].

63. The assessment and classification approach described in this article provides initial guidance on the application of UNFC to base metal tailings mining projects. The approach enables the identification and transparent communication of local sustainability aspects of raw materials recovery projects. This can serve as a basis for discussion on how stakeholders should proceed.

64. For the case study base metal tailings deposit Bollrich, the screening study for desk-based exploration helped to recognise a 'Prospective Project' (E3F3G4). The subsequent very preliminary study based on on-site exploration data is performed from the perspective of all dimensions of sustainability. The UNFC-compliant re-assessment of already existing exploration data helped to identify the potentials of and barriers to project development, and to identify non-economic factors as drivers for raw materials recovery. These driving factors were not apparent before (cf., references [15,26]). The overall project is rated E3.3F3G3.

65. A case study assessment generally provides the opportunity to explore the different options of a project and to determine the next steps. The city administration of Goslar is seeking an opportunity to create high-value jobs and to establish a regional recycling industry [47]. Based on the presented case study assessment, the base metal tailings storage facility Bollrich offers the potential to realise these goals with a sustainable solution including financial benefits. Hence, this study can help the city administration of Goslar to evaluate its options.

66. Overall, the following conclusions can be drawn from the presented case study: (i) the inclusion project benefits and risks at local level in project classification is important due to the frequent proximity to human settlements [33]; (ii) a transparent assessment of raw materials recovery projects requires the consideration of all raw materials, including potentially harmful contents and their impacts; and (iii) a transparent presentation of sustainability aspects can help market actors to better evaluate the risks related to an investment.

67. In a next step, the identified barriers need to be removed by assessing the unclarified aspects to advance the raw materials recovery project Bollrich to a 'Potentially Viable Project' (E2F2G2).

68. In addition, an analysis of strengths, weaknesses, threats and opportunities (SWOT) could be performed to capture UNFC's current development status, and to identify aspects which need to be developed further to make use of UNFC's full potential. In general, it is recommended to develop an approach for a UNFC-compliant preliminary study to provide guidance on the further development of raw materials recovery projects towards their realisation.

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Glossary

73. Terms for raw materials recovery from anthropogenic sources such as tailings are used inconsistently in the literature (e.g., references [55-58]). For the presented case study, the following terms are adapted from reference [14]:

(a) *Tailings storage facility* refers to a physical structure to store tailings in and its contents;

(b) *Tailings deposit* refers to a potential raw material source. Generally, every tailings storage facility is a *mineral occurrence* in exploration terms and can potentially become a mineral raw material deposit [43];

(c) *Target minerals* are intended for valorisation in contrast to the remaining *other minerals*;

(d) *Recovery* refers to the physical extraction of tailings;

(e) *Tailings mining* refers to the whole process from exploration, through recovery and processing to reclamation;

(f) *Screening* is defined as the first desk-based study/assessment to evaluate project potentials and barriers to identify potentially viable projects for further assessment. It is comparable to reconnaissance exploration of mineral raw materials from natural sources;

(g) Following the UNFC's description of the F Categorisation [cf., 16] (p. 6), a *very preliminary study* is regarded as an analogue to a scoping study from the primary mining industry [cf., 50] (p. 31).

Acronyms

AMD: Acid Mine Drainage
CAPEX: Capital Expenditure
CRM: Critical Raw Material
CBM: Gesellschaft für Consulting, Business and Management GmbH
CRR1: Conventional Raw materials Recovery
ERR2: Enhanced Raw materials Recovery
EU: European Union
LMU: Ludwig-Maximilians-Universität München
LOM: Life Of Mine
MFA: Material Flow Analysis
MRE: Institute of Mineral Resources Engineering
NGO: Non-Governmental Organization
NRR0: No Raw materials Recovery
NPV: Net Present Values
NSR: Net Smelter Return
OPEX: Operating Expenditure
SLO: Social License to Operate
SDG: Sustainable Development Goal
UNFC: United Nations Framework Classification for Resources
WWII: Word War II

Chemical Elements

Ag: Silver
As: Arsenic
Au: Gold
Cd: Cadmium
Co: Cobalt
Cr: Chromium
Cu: Copper
Fe: Iron
Ga: Gallium
In: Indium
Ni: Nickel
Pb: Lead
Tl: Tellurium
Zn: Zinc

Chemical Formula/Name of Mineral

$BaSO_4$: Barite
$CuFeS_2$: Chalcopyrite
PbS: Galena
ZnS: Sphalerite
FeS_2: Pyrite