A new mining concept for extraction 
metals from deep ore deposits by 
using biotechnology

Deliverable Number 5.4 – v1.1
Environmental Impact
Assessment of a commercial size 
ISR facility for Cu bioleaching
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With the collaboration of
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EUROPEAN UNION
This project is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 642456.
| **“ D5.4 Environmental impacts from a future full-scale production facility based on in-situ leaching from a stimulated ore body “** |
|---|---|
| **Due date of Deliverable** | 2018-04-30 |
| **Actual Submission Date** | 2018-06-11 |
| **Start Date of Project** | 2015-02-01 |
| **Duration** | 42 months |
| **Deliverable Lead Contractor** | Kemakta Konsult AB |
| **Revision** | Version 1.1 |
| **Last Modifications** | 2018-06-09 |
| **Nature** | Report |
| **Dissemination level** | Public |
| **Public summary enclosed** | No |
| **Reference / Work Package** | WP 5 |
| **Digital File Name** | De-180609-0043 - D5.4 Environmental impacts from a future full-scale production facility based on in-situ leaching from a stimulated ore body |
| **Document reference number** | De-180609-0043 |
| **No of pages** | 117 (incl. cover and annexes) |
| **Keywords** | ISR; EIA; Bioleaching, stimulated deposit |
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BAT</td>
<td>Best Available Technique</td>
</tr>
<tr>
<td>BREF</td>
<td>Best Available Technique Reference Document</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
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<tr>
<td>ERA</td>
<td>Environmental Risk Assessment</td>
</tr>
<tr>
<td>ESAL</td>
<td>Equivalent Standard Axle Load</td>
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<td>EU</td>
<td>European Union</td>
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<td>EW</td>
<td>Electrowinning</td>
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<td>FIGB</td>
<td>Ferric Iron Generating Bioreactor</td>
</tr>
<tr>
<td>GW</td>
<td>Groundwater</td>
</tr>
<tr>
<td>GWDD</td>
<td>Groundwater Daughter Directive, 2006/118/EC</td>
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<td>ISR</td>
<td>In Situ Recovery</td>
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<td>IX</td>
<td>Ion exchange</td>
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<td>MWD</td>
<td>Mining Waste Directive, 2006/21/EC</td>
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<td>NMHC</td>
<td>Non-Methane Hydro Carbons</td>
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<td>NRG</td>
<td>Non-Road Genset Engine</td>
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<tr>
<td>NUTS</td>
<td>Nomenclature of territorial units for statistics</td>
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<tr>
<td>PLS</td>
<td>Pregnant Leach Solution</td>
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<tr>
<td>PM</td>
<td>Particulate Matter</td>
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<tr>
<td>SDI</td>
<td>Sustainable Development Indicator</td>
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<tr>
<td>SLO</td>
<td>Social License to Operate</td>
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<tr>
<td>SX</td>
<td>Solvent extraction</td>
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<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
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<tr>
<td>TMF</td>
<td>Tailings Management Facility</td>
</tr>
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<td>WFD</td>
<td>Water Framework Directive, 2000/60/EC</td>
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Executive summary

This report presents a review of potential environmental impacts from a hypothetical future commercial size plant for *in-situ* recovery of metals from hydraulically fractured deep-lying ores by bioleaching. The review has been carried out as a task in Work package 5 of the BIOMOre project (Horizon 2020 grant agreement No 642456).

The BIOMOre project has focused on developing and testing a technology for *in-situ* bioleaching of sulphidic ores in low-permeability rock in which a solution of ferric iron in sulphuric acid is circulated through the ore deposit causing metals to dissolve. The BIOMOre technology has been tested in the laboratory and in pilot scale in a gallery of the Rudna copper mine operated by KGHM Polska Miedź S.A. It has not been part of BIOMOre project to site, plan or design a commercial scale application of the technology developed. Hence, the present report by necessity builds on assumptions regarding the design and size of the facility as well as about the characteristics of a suitable site for the application of the technology.

The review sets out to follow the formalism of an Environmental Impact Assessment, EIA, according to the European legislation as closely as possible. This involves describing and assessing the significant direct and indirect effects of a possible future commercial size facility for metal ISR on:

- population and human health,
- biodiversity,
- species and habitats,
- land, soil, water, air and climate,
- material assets,
- cultural heritage and the landscape, and
- the interaction between the impacts.

The report contains descriptions of the assumed technical design of a future facility and the characteristics of typical site that would be suitable for application of the BIOMOre technology. It should be emphasised that these descriptions are mere examples. The report also describes potential impacts of the technology in all phases of a facility’s life cycle, i.e. site appraisal and construction, wellfield construction and stimulation, construction of above-ground facilities, wellfield operation, operation of the above-ground facilities, and wellfield closure reclamation. Because of the hypothetical nature of the facility siting, layout and design, the quantitative measures of environmental impacts presented should be regarded with caution. However, the report can be used as a checklist for future EIA work within the licensing of a future ISR-facility based on the BIOMOre technology. Also, within the BIOMOre project, the report will be used as input to the next step of the environmental analysis, a comparison between the impacts of the BIOMore technology and metal extraction by conventional mining.
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1. Introduction

The BIOMOre project is funded by the European Commission as part of the Horizon 2020 research programme (grant agreement No 642456). The project aims to develop methods for stimulated in situ recovery (ISR) of deep ores. The approach involves the hydraulic fracturing of deep low-permeability ore bodies and the subsequent oxidative leaching of the ore using ferric iron and sulphuric acid.

The extraction method developed will only be used on a commercial scale if the environmental impacts are acceptable. Therefore, this report assesses the potential environmental impacts associated with a future commercial scale copper production plant based on the in-situ bioleaching technology developed. The analysis involves all phases of the plant life cycle including construction of the facility, in situ bioleaching and aftercare. The analysis is based on the outcomes of the BIOMOre project, including the laboratory development work (Work Package 1) and the pilot plant (Work Package 3) and uses the modelling tool box developed in Work Package 2. However, it has not been part of BIOMOre project to design or plan a commercial scale application of the technology developed. Hence, the present report by necessity builds on assumptions regarding the design and size of the facility as well as about the characteristics of a suitable site for the application of the technology.

Although the assessment in the present report partly follows the general disposition of an Environmental Impact Assessment, EIA, it is not linked to a formal procedure including a formal EIA. Chapter 3, for example, alternatives for the project are described (A0=no mining, A1=conventional mining and A2=the BIOMOre technology) in way that they should have been described in an EIA. The alternatives A0 and A1 are then not further analysed in the remaining part of the report.

The assessment is based on a very preliminary sketch of a facility design and no specific site has been assign for the localisation of a facility. Therefore, the descriptions in the report of the site, the facility, and alternatives for the process and the siting should be seen only as illustrations or examples and not as suggestions for a future exploitation of the technology.

1.1. The BIOMOre technology

Figure 1 shows a schematic of the BIOMOre technology applied to a copper ore. A lixiviant consisting of sulphuric acid containing ferric iron as oxidation agent is injected into a deep (~1,000 m) metal ore deposit through injection boreholes from the ground. A pregnant leach solution (PLS) is formed by leaching targeted metal(s) from the ore. The PLS is then returned to the ground surface via production boreholes. To increase the efficiency of the ore leaching process, the deposit is stimulated by hydraulic fracturing (“fracking”). During the leaching process in the ore the ferric iron is reduced to ferrous iron. The ferrous iron is oxidised by bacteria in a bioreactor located on the ground and the thus regenerated lixiviant solution is reinjected into the deposit.
On the ground, part of the PLS stream is withdrawn and processed in a metallurgical plant to yield the metal(s) targeted in the operation. A more detailed description of the technology is given in Section 3.4.

The BIOMOre technology has been tested at pilot scale in the Rudna mine in western Poland, which is operated by the project coordinator, KGHM Polska Miedź. The ore was fractured by blasting, whereas hydraulic fracturing is envisaged at a future full-scale production site. The lixiviant is introduced via horizontal boreholes in the upper part of the orebody from where it seeps down through the fractured ore layer and is collected in the extraction boreholes. Copper is stripped from the PLS in a metal stripping unit and then the PLS is fed to a bioreactor where bacteria oxidise ferrous iron to regenerate ferric iron for reinjection. Note that the microbial reactions are intended to take place exclusively in the bioreactor.

The acidophilic microorganisms used in the ferric iron generating bioreactor will be delivered to the pilot plant immobilised on granular activated carbon in a sulphuric acid solution at about pH 2. The consortium includes *Leptospirillum ferriphilum*, *Sulfobacillus sp.* and some *Ferroplasma sp.* (Szubert, 2016). They originate from mining environments and have not been genetically modified nor are they pathogenic. To be active they require very specific environmental conditions related to pH, temperature, carbon source, oxygen content etc. Therefore, while they will function effectively in the bioreactor during the operational phase, they will not be active once the system reaches a neutral or alkaline pH post restoration. They are also expected to be readily denatured on the re-introduction of the naturally saline groundwater or by a harmless solution of acetate (vinegar). This applies also to bacterial colonies that may follow the injected lixiviant into the ore body.
1.2. Modelling tool box FracSim

The modelling toolbox FracSim is the central element of Work Package 2 and the result of the collaboration of several partners in the frame of the BIOMOre project. It is implemented within the software GoldSim™ and is linked to a graphical user interface (GUI), where the user can enter geological and geochemical parameters as well as technological design parameters and economical boundary conditions.

FracSim is a higher level program and steers three reactive transport models in dependency of the selection of the user. These reactive transport models which receive the control parameters from the user interface or from pre-processing units are:

- Integrated PhreeqC Model (Collaboration GEOS and BRGM),
- PhreeqC – Transport Model (Collaboration GEOS, CNRS and BRGM) or
- Reacflow3D (Collaboration GEOS and DMT) with a 1D model approach.

With these models it is possible to simulate experiments for the laboratory scale and the pilot scale as well as the simulation on an industrial scale. As result of the modelling the leaching efficiency will be calculated. Additionally it is possible to simulate the complete sequence of all phases of a full scale plant without interruption.

Further sub modules are the geomechanical tool that forecasts the geometry of the field reactor after stimulation, and the economic module. Figure 2 illustrates the coupling of the sub models in the FracSim toolbox.

1.3. Relevant European legislation

Keith-Roach et al. (2016) reviewed the extent to which the current European legislation supports an environmentally safe application of the technology developed in the BIOMOre project. Some of the main issues identified are discussed below. The main points of this review are briefly summarised below.

**Hydraulic fracturing:** The European Commission (EC, 2014a) identified differences in member states’ interpretations of the conditions under which high volume hydraulic fracturing is allowed. The differences arise from the Water Framework Directive (EC, 2000), which enforces “a prohibition of direct discharges of pollutants into groundwater” although member states may authorise “injection of water containing substances resulting from the operations for exploration and extraction of hydrocarbons or mining activities, and injection of water for technical reasons, into geological formations from which hydrocarbons or other substances have been extracted or into geological formations which for natural reasons are permanently unsuitable for other purposes. Such injections shall not contain substances other than those resulting from the above operations”
This lack of clarity and gaps in European legislation for shale gas fracking led to a recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (EC, 2014b). This recommendation suggests that hydraulic fracturing prior to ISR is allowed under EU law. However, hydraulic fracturing for ISR is not within the scope of these minimum principles. Therefore, legislative gaps remain for hydraulic fracturing for ISR, e.g. for strategic planning, underground risk assessment, well integrity, baseline and operational monitoring, and disclosure of information on chemicals used on a well by well basis.

**In situ recovery:** The mining industry in Europe currently does not use in situ recovery (ISR), thus European legislation and best available technique reference documents (BREF) have not been specifically developed to address ISR in any form and, the guidance in existing BREFs is limited and/or indirect. Also, there is uncertainty in how the process, wastes and emissions fit into the scope of different pieces of European legislation. For example, the leached orebody in ISR does not easily fit the Mining Waste Directive’s, MWD, definition of an extractive waste facility (EC, 2006a). If it is not defined as such, some key protection measures associated with the MWD would not apply, such as the need for a waste management plan to be approved prior to operation, including details of post closure monitoring and control, and the provision of a financial guarantee for the effective closure and restoration of the facility. The MWD also requires measures to ensure that the borehole and well constructions prevent leakage of wastewater, and that the geological, hydrological, hydrogeological, seismic and geotechnical suitability of the site is properly assessed.
Environmental Impact Assessment: The legal definition of the BIOMOre process also affects whether an Environmental Impact Assessment (EIA) is automatically required for smaller operations at the EU level. The requirements of an EIA may also be inadequate for stimulated in situ bioleaching, as the need for a hydrogeological risk assessment is not defined either in the Environmental Impact Assessment Directive (EC, 2014c), the Water Framework Directive (EC, 2000) or the Groundwater Daughter Directive (EC, 2006b).

Site specific baseline monitoring: Relevant site-specific baseline monitoring was also identified as an important gap in current European legislation. Understanding the chemical composition and geochemistry of the baseline groundwater is essential for the later identification of PLS excursions during operation and specification of restoration goals. The requirements given in the Groundwater Daughter Directive are at catchment scale, and are therefore inadequate for this purpose.

1.4. Report structure

Chapter 2 gives a short description of the scope of the EIA presented in this report and an overview of the potential environmental risks addressed. In Chapters 3 and 4 assumed technical process alternatives and assumptions regarding the siting of an ISR facility for metals are presented. Chapters 5 – 10 then presents the assessment of various environmental risks of relevance during site preparation, site operation and site aftercare respectively. Finally, in Chapter 11 some concluding remarks are given in the form of a checklist of issues to be included in a future formal EIA.
2. Scope of the EIA

2.1. Scope and assumptions

The assessment of the potential environmental impacts from the BIOMOre technology has been designed to conform to the largest extent possible to an Environmental Impact Assessment, EIA, according to European legislation on the subject. The EIA should identify, describe and assess the direct and indirect significant effects of a project on population and human health, biodiversity, species and habitats, land, soil, water, air and climate, material assets, cultural heritage and the landscape, and the interaction between the impacts. The impacts on the listed receptors should be assessed “in an appropriate manner, in the light of each individual case”.

This report assumes a case where a potential site for deep (~1000 m) mining has been identified. The first step of the process then is the delineation of the ore body and an appraisal of the suitability of the site for stimulated in-situ recovery, ISR, of value metals. As the present report concerns an assessment of the environmental impacts of a hypothetical commercial size facility this project, the geographic location of the site is not known. Therefore, due to their site specificity, the effects of the operations on receptors (in a typical source-pathway-receptor scheme) is not considered. However, the generic hazardous properties of the identified stressors are considered. As a hypothetical geological setting is assumed in the project, certain characteristics of the site can be considered. These are reported in the site description and utilised in assessment of groundwater related risks.

The unspecified location further dictates that spreading of contaminants (pathway) cannot be fully considered. For instance, spreading of airborne contaminants and spreading with surface waters will not be considered quantitatively due to site specificity (unknown topography, meteorology, and surface water bodies). Spreading of contaminants with groundwater is considered conceptually with certain realistic ramifications that are based on the hypothetical geological setting.

In a formal EIA of a project with a known location, spatial limits of the analysis are specified separately for different stressors based on their mode of spreading (e.g. airborne gases, dusting, spreading in surface waters, noise, vibrations, visual pollution etc.). This is not meaningful in this case.

Economic and employment effects of a project such as this can be estimated to some degree, mainly as direct employment provided by a full-scale facility of the type. However, secondary employment effects and effects on the regional economy cannot be considered. This also limits the usefulness of including the zero- alternative (‘no project’) in the analysis, because the effects of not mining the deposit are mainly economic and social. Similarly, combined impacts with other projects are not considered here even though they are required in a regular EIA because the BIOMOre method itself does not require any large-scale ancillary projects such as construction of large power lines.
2.2. Methodology

The Environmental Impact Assessment in this report is based on the following stages:

- Technical description of the project alternatives with focus on the main features of a future commercial size production site (Chapter 3).
- Description of the baseline conditions of a hypothetical site for *in-situ* recovery operations (Chapter 4).
- Evaluation of the impact of the risks associated with the expected function of the facility and the defined events that can be quantitatively or semi-quantitatively evaluated using the modelling toolbox developed in WP2 and qualitative discussion of risks and impacts that cannot be quantitatively evaluated at present for the different phases of the facility life cycle:
  - Site appraisal and construction phase (Chapter 5).
  - Wellfield construction and stimulation phase (Chapter 6)
  - Construction of above-ground wellfield facilities (Chapter 7)
  - Wellfield operation (Chapter 8)
  - Operation of surface facilities (Chapter 9)
  - Wellfield closure and reclamation (Chapter 10)
  - Overall Environmental Impact Assessment (Chapter 11)

The impacts of the BIOMOre technology will be compared with the impacts from conventional mining in Task 5.5. based on Sustainable Development Indicators, SDIs. Table 1 shows the SDIs that have been selected for this purpose (Keith-Roach and Grundfelt, 2015).

2.3. Environmental Impact and Risk Assessment

2.3.1. Environmental Impact Assessment

Environmental Impact Assessment (EIA) refers to the prior assessment of the environmental impacts of a major project that may have a negative impact on the environment. The projects in question are typically large scale industrial, energy, agricultural, infrastructure, and development etc. projects. The projects may also have positive effects even though it is the negative impacts that trigger the need for an assessment.
Table 1 SDI selected for BIOMOre

<table>
<thead>
<tr>
<th>Aspect</th>
<th>SDI number and title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Performance</td>
<td>G4-EC1 Direct economic value generated and distributed (+ sector additions for mining and metals)</td>
</tr>
<tr>
<td>Materials</td>
<td>G4-EN1 Materials used by weight or volume</td>
</tr>
<tr>
<td>Energy</td>
<td>G4-EN3 Energy consumption within the organisation</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>MM1 Amount of land (owned or leased, and managed for production activities or extractive use) disturbed or rehabilitated</td>
</tr>
<tr>
<td>Emissions</td>
<td>G4-EN15 Direct greenhouse gas (GHG) emissions (scope 1)</td>
</tr>
<tr>
<td>Emissions</td>
<td>G4-EN21 NOx, SOx, and other significant air emissions (+ sector additions for mining and metals)</td>
</tr>
<tr>
<td>Effluents and Waste</td>
<td>G4-EN22 Total water discharge by quality and destination</td>
</tr>
<tr>
<td>Effluents and Waste</td>
<td>MM3 Total amounts of overburden, rock, tailings, and sludges and their associated risks</td>
</tr>
<tr>
<td>Local communities</td>
<td>G4-SO2 Operations with significant actual and potential negative impacts on local communities</td>
</tr>
</tbody>
</table>

EIA is essentially a decision-making tool that allows proper consideration of the main environmental impacts of a project before any major decisions or commitments have been made. In an EIA, the decision making is built in the structure of the assessment in the form of project alternatives one of which is always the so-called zero alternative of not proceeding with the proposed plan. The zero alternative is also the one against which the positive impacts of the other alternatives are compared. In most jurisdictions, including the EU, carrying out an EIA is mandatory for major projects with expected negative environmental impacts. Legislation and regulations typically govern the EIA process and public participation and commenting is usually an integral part of the administrative procedure.

Because EIAs are carried out well before the project has been realised, the assessment cannot rely on measured data on the impacts. The assessment must, therefore, start with the planned and designed properties of the project that may cause environmental stress in the form of emissions (gases, dust, waters, noise, light, heat, vibrations, biological etc.), wastes, visual impacts, land disturbance, hydrological or hydrogeological effects, regional economic and demographic effects etc. The magnitudes and properties of these stressors are considered for the typical operating conditions of the facility in question. It is also assumed that all emission mitigating methods are functioning as designed (e.g., water treatment, gas scrubbers). Failures and other excursions from the normal operation are considered in an EIA as well, although the emphasis is on the impacts of the regular operation. Non-local effects are considered in the form of GHG emissions and energy and water consumption. In all cases, methods to mitigate the impacts are discussed.

EIA aims at incorporating environmental values in the decision making on large projects such as mining projects. It is, therefore, of very practical nature rather than a thorough analysis of all possible impacts. It is recommended practice to first identify all the potential impacts of the project and then concentrate the assessment efforts and resources on those effects that are likely to be significant. For the sake of public
and official scrutiny, this process of selecting the most significant effects should be well documented. In some cases, it is advisable to also study certain less likely effects in more detail if they cause public concern during the EIA process. In the case of the BIOMOre method, for example, human health effects of bacteria injected 1000 m below the ground surface might be one such example.

At the end of the EIA process, the significance of the various stressors is assessed once more and the effects are compared. Similarly, the impact profiles of the project alternatives are compared, often with the help of a tabular presentation. Informed decisions that take the environmental factors into account should then be possible.

2.3.2. Environmental risk assessment

Environmental risk assessment and environmental impact assessment have much in common. They both look at the adverse consequences of a stressor (called hazard in risk assessment) for a receptor (or assessment endpoint). Like EIA, Environmental risk assessment (ERA) incorporates both ecological risk assessment and (human) health risk assessment.

In contrast to the project-specific practical decision support concept of the EIA, ERA is a systematic approach to quantifying the risks related to a hazard in a scientific manner. While EIA emphasises the impacts of the normal operation of a facility or a project, risk assessment looks at the variability and also uncertainty in the data to estimate the likelihood that a hazard causes harm of a certain severity to a receptor via exposure. Risk assessments often study single hazards, such as chemical substances, during their intended use. Estimating exposure to the chemical or other hazards is thus an integral part of risk assessment.

EIAs may involve detailed risk assessments of some key hazards related to the project. In the documentation of the EIA (EIA statements or reports), these detailed studies are placed in appendices and their main findings are utilised in the EIA statement.
3. Technical description of the project alternatives

3.1. Formulation of project alternatives

Regular EIAs should present project alternatives, including a no-action alternative (0 alternative) whose environmental impacts are then compared. The alternatives should be realistic and economically viable. The latter is important because premature closure typically involves environmental, economic and social risks. It is often possible to define more than one viable project alternative that will differ in technical solution or scheduling and, hence, in environmental impacts. In Sections 3.2 and 3.3 below, possible alternatives are outlined. However, these are not further analysed in this report.

3.2. A0 No mining

The “no mining” alternative is typically used to illustrate the future development of the site and the region if the project is not implemented. The effects are thus mainly economic and social in nature. For instance, this scenario looks at the predicted development of employment and population in the absence of the mining project. These data can be used as the baseline scenario to assess these types of effects of the mining project. In this case, the exact location of the mine is not known and therefore the no mining scenario is not explicitly addressed here.

3.3. A1 Conventional mining

Deposits of the type concerned in BIOMOre are being mined with conventional methods as well. In these operations, shallower strata (e.g. at 600 m) are mined first and mining then proceeds deeper, down to depths considered in BIOMOre (~1000 m) and even deeper (1200-1400 m).

The following sections are mainly based on an evaluation report by Micom (2013) on the KGHM mining operations in Poland. These data are used to describe a hypothetical conventional underground mining operation that utilises these types of ores.

3.3.1. Mined strata

Conventional mining utilises all three types of mineralised rocks typical to the Kupferschiefer deposits: Sandstone Ores in the upper part of the White sandstone (Weissliegendes), Shale Ores in the Black Shales and the bordering dolomitic rocks; and Carbonate Ores in the dolomitic and limestone strata above the Shale Ore zone. The Shale Ore in particular also contains silver that also is recovered with the copper and is important for the cut-off grade of the ore.
3.3.2. Exploration drilling

The properties and spatial arrangement of the deposit to be mined need to be known for both In Situ Recovery and conventional mining. In addition, geotechnical rock properties need to be studied outside of the ore zone for the adits, raises, ramps, shafts and other underground openings that are driven for conventional mining. This is done using geophysical methods and drilling. While the use of geophysical methods causes little or no disturbance to the environment, drilling may create noise, dust, exhaust gases and solid waste materials. It also consumes energy and some water.

While all exploration drilling for BIOMOre-type operations is done from the ground surface, drilling is continued from underground in conventional mining. Both methods require detailed enough (closely spaced) drilling for estimation of resources and reserves but some of the drilling to guide mining can be done underground for the conventional method.

3.3.3. Mining

The conventional mining process can be broadly divided into three phases: underground access (driving of inclines and shafts to reach the desired level), ore access (driving of levels to access the ore body), and production mining (room and pillar mining). Mining is done in a drilling and blasting cycle: surveying and drilling of blasting holes (electro-hydraulic drilling jumbos), charging the basting drill holes, blasting and ventilation of the gases, loading and hauling of the blasted material (diesel powered load-haul-dump machines and trucks), and ground support (rock bolting etc.). After this, the cycle starts over.

The ore body is mined with room and pillar mining. In this type of mining, rooms and cross cuts (at right angles to the rooms) are first driven to the ore body from access shafts, leaving rectangular pillars for support. In a second mining phase, the size of the pillars is reduced from all sides, leading to 75-90% of the ore being removed. The mining areas are then sealed and allowed to cave in naturally. In some cases, however, hydraulic sandfill or backfilling with waste rock is employed, depending on the thickness and dip of the ore and on the overlying structures. Thickened tailings can also be used as paste backfill material (Micom, 2013).

Conventional mining employs shafts for production, ventilation, and transportation. All drifts needed for utilizing the ore are located in the mineralised levels to minimise generation of waste rock. The mined ore is hauled by truck or loader to a rock breaker/feeder (size reduction station) and transported by conveyor belt or rail to a hoisting shaft. On the surface, the ore is transported by conveyors to the enrichment plant.

In these types of deposits, water inflow to the workings is low. However, a certain amount of dewatering pumping is needed and when the workings are extensive, the amount of pumped water increases. This can also lead to the formation of a groundwater depression cone. The pumped waters are saline, containing sulphates...
and chloride and other dissolved solids with a TDS in the range 3000 – 370 000 mg/l (Mizera, 2013). In some cases, the overlying dolomite and limestone beds form aquifers that can cause short term inflows on water. These are stored in retention ponds before pumping. All of the water that is pumped from the underground is used to prepare hydraulic backfilling or for minerals processing.

Underground workings require ventilation and cooling. The temperature gradient in this deposit type is 1 °C per 32 metres, with 35 °C at 850 m and 46 °C at 1,200 m. Mining facilities are ventilated with ambient air. In addition, chilled water refrigeration plants of 10-15 MW are required for cooling the deeper levels of the mine. Also, air-conditioned cabs are used in mining vehicles at the deeper levels.

3.3.4. Mineral processing

Mineral processing of the mined ore is done with conventional froth flotation. The ores are first crushed to the specified size, then milled and classified using spiral classifiers in the grinding circuit until it is suitable (~45 µm) for xanthate-based froth flotation. The flotation circuit consists of five to six flotations with classification using hydro cyclones and ball mill regrinding as necessary. The material stream to final tailings is from the rougher-scavenger unit. The concentrate is treated in gravity thickeners and filter presses before thermal drying to produce the final concentrate (Luszczkiewicz and Chmielewski, 2008).

3.3.5. Tailings management

Tailings from the flotation process are pumped as a slurry to a Tailings Management Facility (TMF) that is dammed above ground level. The tailings dams are of seeping type and the seepage is collected and returned to the TMF. Supernatant water after the settling of solids in the TMF is collected and partly recirculated to the mineral processing plant. Any excess supernatant is discharged to receiving surface water bodies (river) either directly (clear water fraction) or after treatment to remove solids (high solids supernatant). It should be noted that drying the tailings by filter presses before transfer to tailings dams has become a standard and is required in several countries.

There are some sulphides left in the tailings that can cause acidification after deposition if allowed to oxidise. This acid rock drainage will lead to further release of metals to solution from other minerals as well. This is prevented by keeping the tailings water saturated during the operation of the TMF and progressively covering the facility upon closure. A multi-layer dry cover will be used that reduces the ingress of oxygen and water to the tailings surface and generates alkalinity to counteract any acidity that may be released.
3.3.6. **Downstream processing**

Unlike in situ recovery, conventional mining produces a concentrate composed of the original ore minerals. The valuable metals contained in these minerals need to be liberated with leaching or smelting before they can be purified. Downstream processing of the mill concentrates from mines of this type involve smelting. Outokumpu-type flash smelting is BAT for this type of operation. In short, smelting involves drying and blending of the concentrate, flash smelting in a furnace to produce blister copper, casting copper anodes after melting in anode furnaces, and producing cathode copper in an electrolytic cell. The flash smelting slag also contains some copper so it is remelted in an electric furnace to produce a Cu-Pb-Fe alloy. The alloy is treated in converters to produce blister copper that is taken to anode production similar to the original flash smelting blister copper.

The downstream treatment of the final products from BIOMOre type ISR mainly involve hydrometallurgical treatment. This part of the process is not treated in this EIA. Therefore, the downstream processing of the mineral concentrates from conventional mining are not discussed further.

3.4. **A2 In-situ stimulation and biomining applying the BIOMOre technology**

3.4.1. **Model of a full-scale ISR facility based on the BIOMOre technology**

The model full scale facility is constructed by drilling into a copper deposit and applying hydraulic fracturing to increase the permeability of the ore horizon. Following an initial phase of water washing and acid treatment of the ore to remove chloride and carbonate rocks, a sulphuric acidic solution containing bacterially-oxidised ferric iron will be used to leach the fractured ore body. The ferric iron solution will be generated and regenerated in a bioreactor located at the land surface and injected into the ore body via injection wells. Metal-containing sulphide minerals in the ore deposit will be oxidised by contact with the lixiviant, and the metals released will be maintained in solution because of its high acidity. Ferric iron will be reduced to ferrous iron during the reaction. The metal-laden pregnant leaching solution will be pumped to the surface, target metals extracted and the iron re-oxidised in the bioreactor before again being injected into the ore body.

Figure 3 shows a schematic flow sheet over the life cycle of the BIOMOre *in-situ* bioleaching process including the following phases:

- Construction and well field preparation phase (red oval in Figure 3) – Drilling and building wellbores for injection of lixiviant and extraction of PLS from the surface to the depth of the ore body followed by horizontal drilling in the orebody and hydraulic fracturing (stimulation). Pumping to establish hydraulic gradients, washing with water to flush out detrimental chlorides and leaching of carbonate rocks using acid.
• Bioleaching production phase – Introduction of lixiviant through injection wells and collection through extraction wells, metal stripping and bacterial regeneration of leaching agent.

• Post-production treatment (blue oval in Figure 3) – Site aftercare including washing, neutralisation, sterilisation and monitoring the hydrogeological restoration and long-term safety.

Figure 3 Schematic flow sheet of the BIOMOre copper production process. The red oval encircles process steps involved in the construction and preparation of the well field. The blue oval encircles the post operation phase. Outgoing arrows indicate product streams and potential emissions from the process.

The main requirements for a commercial size ISR facility for copper extraction are:

• Drilling and hydraulic fracturing equipment.
• Means for handling drill cuttings.
• A well field consisting of wells drilled from the surface to the ore horizon at a depth of 1000 m or more. Some of the wells will be injection wells and some will be extraction (production) wells.
• A surface facility containing equipment for stripping of copper from the PLS, copper production from the stripping solution and, microbial regeneration of the ferric iron.
• Effluent treatment facilities including tanks and ponds to store excess process solutions and water. The volumes of these must be sufficient to buffer foreseen events and disturbances.
• Facilities for treatment and destruction of process waste including waste from drilling and preparation of the well field.

Figure 4 shows a schematically the principles of an ISR facility for copper extraction. Only the equipment used in the bioleaching production phase of the facility life cycle is shown.

![Schematic of a commercial size in situ copper bioleaching facility.](image)

*Figure 4 Schematic of a commercial size in situ copper bioleaching facility.*

The surface facilities of an ISR operation based on the BIOMOre bioleaching technology would include (see Figure 4) a pump station/well house, settling ponds and/or a filter house, a ferric iron generating bioreactor (FIGB), a metal stripping facility and a waste treatment facility. In addition, auxiliaries like a laboratory, office buildings and a power supply are needed.

In the pump station/well house the injection of lixiviant and extraction of PLS is handled. Fines like clays and precipitates in the extracted PLS are removed in the filter house alternatively in settling ponds. A filter house is often the preferred solution as colloidal particles tend not to settle efficiently in ponds. As the leached part of the ore body becomes depleted, the well house and the filter house will be shifted and new
wells drilled. The disused wells will be remediated and decommissioned, and the land will be reclaimed.

3.4.2. Drilling, deposit delineation, and characteristics

Like in conventional mining, an ISR project begins with exploration drilling with assaying and geophysics to locate ore bodies (resources). The deposit is then drilled and cores and wells are logged further, resulting in a denser drilling grid, to delineate its 3D extent in more detail. Because the aim is to recover the ore in situ using a lixiviant, the mineralogical, geochemical and hydrogeological properties of the deposit and the site are studied to build a complete 3D model of the deposit and its surrounding strata, including stratigraphic details, structural elements such as natural fracture networks. In addition, the petrophysical and rock properties that affect the stratum's response to hydraulic stimulation are studied from core logs, well logging methods and surface geophysics. The aim is to gain an understanding of the mineralogy, lithology, relative rock brittleness, natural fracturing, and the directionality of the in-situ rock stresses (Holden et al., 2013).

The data that can be obtained from the drillings and surface or down hole geophysics are used to create a hydrogeological model of the site (background hydrology). This information is needed not only for the hydrological modelling of the leaching process but also for modelling the post-mining clean-up phase of the formation that is partly based on natural attenuation.

The information gained on the rock properties are used to plan the stimulation process and to predict the outcomes of the stimulation. These data are used with information on typical ranges of injection and collection parameters (pressure, flow) to create first hydrological models of the leaching phase and to assess the well geometries.

The leaching modelling not only needs hydrological parameters but also information on the mineralogy, geochemistry, and the kinetics of the mineral reactions. This is because the aim is to optimise the leaching process and allow for a long enough reaction time for effective leaching.

3.4.3. Site preparation and construction

After the deposit to be mined and its properties have been delineated and modelled in 3D, the siting of the above-ground facilities can be planned. While there are limited possibilities for siting of the well field, environmental considerations can be considered in the placement of other functions of the facility. These include the process control, administration, lab, maintenance and workplace facilities building(s), storage facilities, metal recovery and refining facilities, effluent and waste treatment facilities and structures, bioreactor (FIGB) facilities, and ponds and reservoirs for lixiviant and PLS.

The well field is constructed with minimal land clearance and earth construction. The production wells are drilled according to the primary stress field at the deposit level.
Directional drilling is employed and the section of the wells in the production zone is horizontal. The planned curvature (3.5 deg/100 ft) means that the above-ground part of the well is approximately 450 m away from the edge of the production zone, in either of two possible directions. An access road capable of supporting heavy drilling machinery is built to facilitate all drilling locations. On-site power lines are drawn along the access road and major power lines from the main grid are constructed according to pertinent guidelines. If needed, a separate EIA is carried out for the power line.

The pipelines required for the well field, including trunklines to and from the other facilities, are constructed above ground with minimum land clearance and removal of vegetation. Inspection and maintenance of the pipelines and operation of manual valves requires vehicular access with at least ATVs along the length of the pipelines, however, and this is taken into account in the construction. The trunklines are permanent pipelines that are not moved along with the proceeding wellfield across the deposit whereas disposable plastic pipes are used for pipelines from individual wells (or wellhouse, if the wells in production are housed in a sheltering building with filtration facilities).

3.4.4. Drilling of ISR wells

Much of the discussion on drilling, perforation, and stimulation below is derived from the BIOMOre report Technological Aspects of Drilling, Perforation, and Stimulation by Dieterichs et al. (2017).

Injection and production wells are drilled in doublets using either two single wells (own borehole from the surface for both wells) or a multilateral configuration (shared vertical parent wellbore). In both cases, the vertical section extends down to 1045 m and the 890 m long horizontal part of the injection (upper) well lies at 1544 m. The production well is placed 20 m below the injection well and has a length of 910 m.

The wells are drilled with a large DC electric operated top drive drill rigs. Power is generated using two modern CAT 3521E generator sets that can adjust the power output flexibly according to the power demand. Above-ground steel tanks are used as mud pits instead of pits dug and lined into the ground to generate as little as possible of land disturbance and to minimise any spillage events. Due to the scarcity of shales in the overlying rocks, a fresh water based mud is used as the drilling fluid (mud) with sand, active clays, and barite as the main additives.

A preliminary design of a wellbore is indicated in Figure 5. The target ore horizon is assumed to be in a sandstone layer (Rot- und Grauliegender Sandstone). The ore horizon is covered by an aquitard consisting of a limestone and an evaporite layer that, in turn is overlain by the Buntsandstone layer and cenozoic sediments. The wellbore is lined with a cemented casing down to the limestone layer where the drilling is turned to horizontal following the ore horizon.
Figure 5 Preliminary proposal for borehole design in an ISR facility for metal extraction based on the technology developed in BIOMOre. Dimensions: 16” ≈40.6 cm, 13⅜” ≈34 cm, 12¼” ≈31.1 cm, 9⅝” ≈24.4 cm, 8⅜” ≈21.6 cm, 7” ≈17.8 cm.

The horizontal portion of the borehole is lined with a production liner and the annular space between the production liner and the borehole wall is filled with cement. Figure 6 shows a tentative multibranch design of the horizontal part of the wellbore. It is recommended to drill the horizontal part of the borehole in the direction of the minimum principal stress and with a maximum length of 900 m (Jatho et al., 2015) and to initiate fractures every 20 m. Based on fracture geometries simulated by Weber and Yildizdag (2017) using the FLAC3D code a suitable spacing between the branches would be in the range 20 – 50 m. Holes should be drilled at two levels with the injection holes located at the higher level and the extraction holes at the lower level. Typically, an ISR facility has twice as many injection wells as extraction wells.

A well field of an ISR facility needs to be surrounded by a suitable number of monitoring wells, see Figure 4. These constitute a safeguard against excursions of lixiviant and other disturbances outside the mining area.
3.4.5. Stimulation

The hydraulic fracturing could be performed by the so-called plug and perforate technique illustrated in Figure 7. After the wells have been drilled, casings have been run and cemented, the lowermost horizontal part with the production liner is perforated and hydraulic stimulation is carried out. The perforating jet guns are lowered to the end of the long, horizontal pay zone using coiled tubing equipment that allows conducting perforation and stimulation in deviated wells. A high perforation density (e.g., 14 shots/m) is, despite the increased cost, applied due to the low permeability of the deposit. Low gun clearances are achieved by deflectors but it is possible to attempt to mostly perforate the lower part of the injection well by letting the gun rest at the bottom of the hole if injection above the hole is not desired.

Hydraulic stimulation is carried out after a zone of suitable length has been perforated. In principle, the whole well section to be perforated and stimulated lies in the pay zone so that zonal isolation is not necessary to avoid certain strata. Rather, zonal stimulation is used for technical reasons to optimise the speed of the stimulation operation.

In hydraulic stimulation, a fluid is injected under high pressure through the holes and initial cracks generated in the perforation step. The wells will be drilled in a direction that either follows the major stress direction in the formation or is perpendicular to it. Fractures typically propagate normal to the minimum principal stress direction, resulting in either transverse or axial fractures (relative to the drill hole direction) if holes are drilled according to the stress field direction. To keep the fractures open, proppant materials are injected with the fracturing fluid. Based on the properties of the deposit being fractured in BIOMOre-type operations (long perforated intervals, low permeability, shale formation, low pressure gradient) borate-crosslinked or organometallic-crosslinked stimulation fluids will be used. When acid and water washing is used, proppant is added only after these stages. Local sources of fresh water are used if possible to minimise tanker truck traffic to and from the site.

Figure 6 Tentative design of a multibranch horizontal borehole. The length of the horizontal bore is up to 900 m with a separation between the branches 20 – 50 m. (Weber and Yildizdag, 2017)
3.4.6. Pre-treatment for the leaching step

When the injection and production wells are in place, cased and cemented, and hydraulic stimulation has been completed, the formation to be mined is leached of excess acid buffering minerals and flushed of chloride. The former is done to improve the eventual leaching that is partly based on acidification of the deposit while the removal of chloride is done to protect the bacteria in the bioreactor that cannot tolerate elevated levels of chloride.

The leaching of carbonates is done by injecting a sulfuric acid solution to the formation and recovering it through the production wells. This acid washing step is not similar to acid fracturing as acid is not used to create or widen fractures – only to dissolve the most readily reactive carbonates. During the washing step, the formation and injection pressures are monitored because CO₂ gas may build up in the formation upon dissolution of carbonates, and gypsum precipitation may clog the fractures to reduce permeability. At the end of the acid flushing stage the dilute acid is exchanged for fresh water to lower the amount of chloride in the formation. The acid washing waters are treated with lime to precipitate any metals that have leached. If possible, the flushing steps are also used as pumping tests and the hydrological/reactive transport model for leaching is updated accordingly for better control of the leaching parameters.
3.4.7. The in situ leaching step

After the preparation steps, the ore formation is leached with a lixiviant containing the inorganic, non-oxygen oxidant Fe(III) in a sulphuric acid solution. The pH of the lixiviant needs to be low enough to keep the iron in solution (pH below 2.3). The lixiviant is injected to the hydraulically generated fractures from the injection wells at the top of the ore body. The solution migrates by gravity through the ore and reacts with the copper sulphide minerals to liberate copper. The thus generated PLS is collected by pumping from the collection (production) wells at the bottom of the ore body. A slight excess of collection pumping is maintained and some fresh formation water is pumped with the leaching solution so that no lixiviant migrates outside of the planned and modelled leaching zone. Observation wells are placed around the in-situ recovery zone to identify any lixiviant excursion.

3.4.8. Lixiviant regeneration

During leaching the ferric iron in the lixiviant is reduced to ferrous iron. The ferric iron is regenerated in a bioreactor (FIGB, Ferric Iron Generating Bioreactor) with an active culture consisting of acidophilic strains of mesophilic or moderately thermophilic or thermotolerant bacteria and archaea. Several reactors operated in parallel will be needed to treat the volume of PLS. The reactors themselves would be about 7 metres diameter and about 10 metres tall. Each reactor will host about 26 tonnes of activated carbon carrier. Air will be injected at the bottom of each reactor at a rate of 65 tons per day, thereby causing the fluidisation of the carbon and biomass. The operating temperature of the bioreactor is normally about 32°C and the pH about 1.3. A variation of a few degrees can be tolerated. If the mine is in an extreme climate location, the reactors may need to be insulated or installed inside a climate controlled environment.

The solution is pumped to the bottom of the reactors and overflows at the top. The tops of the reactors are fitted with very fine screens to avoid the loss of carbon by entrainment in the overflowing solution.

3.4.9. Metal recovery

The regenerated solution is recirculated through the ore deposit multiple times until the copper content is sufficient high (>10 g Cu/l) to withdraw part of the PLS stream to the metallurgical plant. The first step in the metallurgical plant is pre-concentration of the PLS stream. The pre-concentrated PLS stream is then stripped of its content of the target metal.

Within the BIOMOre project various membrane technologies have been reviewed (Hatch Associates Ltd., 2017). The review gives focus to nano-filtration applications due to its process flexibility and cost advantages over reverse osmosis. Based on a modelling exercise it was concluded that, for a PLS composition representative of BIOMOre conditions, the copper concentration factor in the range three to ten could be expected given that the risk of membrane fouling due to gypsum scaling could be...
properly managed. This would involve the application of novel technologies such as, for example, micro-bubbles, ultra-sonics or magnetic fields.

An evaluation of the potential economic viability of alternative flow sheets for the stripping of metals from a PLS of a composition expected from the application of in-situ bioleaching of Polish Kupferschiefer ore was performed by Hatch Associates Ltd. (2016). The results show that three flow sheets had potential to be economically viable:

- Sequential sulphide precipitation,
- Recovery by ion exchange preferentially followed by electrowinning. Ion exchange followed by sulphide precipitation could possibly also be viable.
- Recovery by Solvent Extraction followed by electrowinning.

Copper was only metal that potentially could be economically extracted using the above listed techniques. The reason for this is that the PLS expected from the Polish Kupferschiefer ore is rich in copper but poor in other metals. The results of a similar analysis would likely be different with an ore body yielding a different composition of the PLS.

3.4.10. Waste water treatment and discharge or disposal

The metal recovery step will result in a product stream containing the value metal, a stream of stripped PLS that will be transferred to lixiviant regeneration, and some waste streams.

In the ISR process, slightly more solution is drawn in from the recovery wells than is injected. This produces excess solution that need to be treated. In uranium ISR facilities, this excess volume can typically amount to about 1 to 3 percent of the circulation rate (NRC, 2009). The BIOMOre project has not explicitly studied the arisings of waste streams from the metal recovery plant. It is therefore not possible at this stage to estimate the amounts of effluents and waste arisings. The process descriptions below should be seen as examples only.

The waste water treatment will focus on the removal of metals and other toxic elements (e.g. As and Cd), and neutralizing the acidic waste stream. After the copper and iron recovery processes, copper will be further removed from the waste water stream by adding sulphide, e.g. in the form of sodium sulphide, to the waste solution under slightly elevated temperatures (40-50 °C).

Zinc, nickel, cobalt, manganese, and magnesium can be precipitated by adding sodium carbonate. It is possible to recover these metals independently as saleable metal concentrates, if the sodium carbonate is added gradually at elevated temperatures and the process runs slowly (small stream of the precipitant and intensive mixing). This on the other hand means that the process might not be
profitable enough from an economical perspective as it substantially lowers water treatment capacity. In this case, the metal concentrate is likely discarded though pit burial.

The remaining excess water can be discharged to an evaporation pond and/or a deep well injection for disposal, or treated further for discharge to the environment (NRC, 2009). Sludge remaining after evaporation will be discarded by pit burial. The pit will be fitted with a polymer liner and slope integrity will be one of the key elements during its design. The pit should be located above groundwater table. If water has accumulated on top of the pit before its burial, the water should be discarded through evaporation ponds and/or injections. After that, the pit will be covered with clean soil material and re-contoured (Aird, 2008).

3.4.11. Wellfield closure

As the leaching zone of the ore deposit becomes depleted, the well field will be decommissioned and the operations moved to a new position. The decommissioning will involve remediation and sealing of the disused well field. The well remediation will typically involve denaturing of the groundwater by injecting a suitable bacteriocidic solution, sealing off open fractures by, for example, chemical precipitation, cleaning the mining zone by flushing and sealing off the hole.

Schippers and Ballerstedt (2017) suggest for the denaturing step a mixture of formic acid, 1-hexanol, sodium chloride and sodium dodecyl sulphate. Experiments indicated that replacing the formic acid with acetic acid would give a less efficient denaturing solution. For the fracture sealing, injection of a calcium chloride solution was suggested to precipitate gypsum in the fractures.

After denaturing, the mining zone is flushed with baseline quality groundwater. This is achieved by pumping water from all production and injection wells without re-injection. The in-rush of native groundwater cleans the production zone of dissolved metals and remaining leach solution (NRC, 2009). The entire volume of the production zone is pumped multiple times over and the chemical quality of water is monitored simultaneously. The active treatment step is followed by a monitoring stage, which can be expected to last anywhere from months to years. Monitoring includes at least quarterly water samples where the chemical stability of the production zone is verified.

Once the monitoring period has been concluded, production- and injection wells will be filled with concrete to limit migration of possible left-over contaminants and to block un-natural flow paths of groundwater. On ground surface the well field structures will be dismantled. Above the ground well casings are cut to a suitable length and capped, ground
4. Present state of the site

The location of a future commercial size production plant based on the BIOMOre technology has not been decided. In the present report, it is assumed that the technology will be used to exploit a deposit similar to the formation where the experiments are conducted in the BIOMOre project, i.e. within the Kupferschiefer formation. This assumption has been made only to facilitate defining reference site properties such as climate, geology, hydrology and hydrogeology, biota, and built environments and inhabitants.

The area of the Kupferschiefer formation is extensive, stretching through the whole of Central Europe under the North Sea and north along the coastline of United Kingdom, Figure 8. The term Kupferschiefer is partially misleading as economic concentrations of other metals than Cu, notably Pb, Zn, Ag, along with elevated levels of Co, Ni, Re and Au, also are encountered within the formation. Figure 9 shows the area where Cu ore or potential Cu ore zones have been predicted (Royer et al., 2013).

![Figure 8 Total extent of the Kupferschiefer –formation. Based on Borg et al. (2012).](image)

As the location of a future production site is not defined, the present state of the site can only be described in a very broad way. The site is expected to be located somewhere in the eastern part of Germany or western half of Poland, within the largest predicted area of elevated Cu concentrations. Characteristics of the hypothetical site are in some cases described based on a reference location – a German town called Weißwasser, located in Upper Lusatia in eastern Saxony, just a few kilometres from the Germany-Poland border.
4.1. Climate

According to the commonly used Köppen climate classification, the site would likely hold either Marine west coast climate (Cfb) or Humid continental climate (Dfb) depending on its actual location. Both climates are similar, but in the marine climate winters are slightly warmer and annual rainfall is higher than in the continental climate.

The reference weather conditions are described based on the Weißwasser reference location. The annual average temperature is around 10 °C. The warmest month of the year is July, with an average temperature of approximately 19 °C. January is the coldest month of the year, at approx. -1 °C, see Figure 10. Seasonal differences in precipitation are small. The driest month is February, with approximately 30 mm of rainfall. In July, the precipitation reaches its peak, with an average of 70 mm, Figure 10. In the Weißwasser area, annual effective precipitation (precipitation-evaporation) varies between 200-300 mm, while the total precipitation is roughly 600 mm.
4.2. Geology

The Kupferschiefer is a non-metamorphosed and non-foliated sedimentary rock unit. The unit is thin, commonly only about 30 cm thick, black, and rich in organic carbon. Stratigraphically, it resides at the base of the Zechstein succession, just above the sandstones of the Rotliegend group. However, the location of the copper mineralisation in relation to stratigraphy varies throughout the region. For example, in some parts of Poland the black shales of the Kupferschiefer cannot be observed at all, yet the copper mineralisation still exists in either Zechstein or Rotliegend layers (Borg et al., 2012).

The geological structure of German-Poland border region is complex (Figure 11) and some of its properties are not optimal for the ISR method. For example, the black shale of the Kupferschiefer formation is commonly overlain by limestone that can dissolve during the leaching process resulting in high acid consumption. In addition, the cap rock is not uniform and massive in many areas but has discontinuities such as cracks and faults that may provide unwanted flow paths for process waters. Graben structures are typical of the region. However, these issues are taken into consideration in the selection of the site.
In the first instance, the BIOMOre technology is intended for use at depth, where traditional mining becomes restrictively difficult and expensive. For the technology to work effectively, the ore horizon should consist of a relatively permeable host rock with a low carbonate content. Higher permeability increases the likelihood of an effective leaching procedure after hydraulic fracturing, while low carbonate minimises the loss of acid and the production of gas and precipitates. The ore horizon should be well separated from potable aquifers by an aquitard consisting of low permeability rock.

The geological setting assumed in this EIA is informed by the findings in the pilot experiments in the Rudna mine in terms of the role of groundwater salinity and presence of carbonate rocks and, in addition, by the stratigraphy in the ProMine/BIOMOre model of the North Sudetic Trough. The ore is assumed to be leached from depths below or around 1 kilometre because at shallower depths it is likely to be more profitable to utilise traditional underground mining. The ore deposit itself is assumed to be 100 metres thick to allow stimulation by hydraulic fracking.

For the EIA, the geology at the theoretical project site has been simplified to make modelling and impact assessment feasible. In the simplified stratigraphy, the first 100 m below ground surface consists of permeable and fully saturated sedimentary layers of Quaternary age. The Quaternary layer is separated from the underlying Buntsandstein aquifer by a loam/mudstone aquitard. The Buntsands tein aquifers are
underlain by an aquiclue consisting of limestone/dolomite and rock salt formations acting as a cap rock for the ore horizon. All rock contacts are assumed to be perfectly horizontal and sharp.

4.3. Hydrology and hydrogeology

In Germany, two-thirds of the population use groundwater for their water supply. Also, in Central Europe the use of aquifers for other uses such as geothermal energy or heat energy storage widespread. Groundwater resources can be hosted in several kinds of different and unique formations. For example, 49% of Germany, is underlain by porous aquifers, about 12% is underlain by fractured aquifers and 6% by karst aquifers. In the northern parts of the country, aquifers are mainly hosted in glaciofluvial sand and gravel deposits while down south aquifers are commonly held in gravel filled valleys of the Alps. Bedrock and karst aquifers are unique and highly variable. Water movement in such formations is typically non-uniform and characterised by erratic heterogeneity and non-horizontal making groundwater flow modelling very challenging (Neuman, 2005; Faybishenko and Benson, 2000).

Different kinds of aquifers are also present near the reference area of Weißwasser. In this area the groundwater is extensively used as tap water. The groundwater utilised are in shallow deposits of Quaternary and Tertiary age. In the higher regions north of the town, the aquifers used are hosted in sand formations. Near the town itself, they are most commonly seen in gravel-filled valleys, while to the south, till formations (capable of holding substantial amounts of groundwater) are common. The rate of groundwater regeneration also varies considerably (from approx. 10 to 250 mm/a), depending on the ground cover material and the type of the aquifer. Flow rates vary from slow (>1x10^-5) to moderate (~ 1x10^-3). There will be a substantial thickness of rocks between the aquifers utilised and the operating depth of an ISR facility.

The waters in the aquifers used have been noted to vary in hardness ranging from 0 to 30 °dH. Total dissolved solids commonly vary between 200 and 350 mg/l. Cations are largely defined by the alkaline earth metals, with Ca and Mg being the most common, and Be, Sr, Ba and Ra often observed only as trace elements. The anion

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content, however, can vary between locations. Some waters where sulphate is the dominating anion have been observed north and south from the potential project site location\textsuperscript{2}. Many shallow German aquifers are anthropogenically influenced. Shallow aquifers near the reference project site are expected to be of good quality as defined by the Groundwater Directive (EC, 2006b) and to show no major signs of human interaction.

The groundwater conditions at the reference project site have been simplified. The main usable aquifer is located in the unconsolidated Quaternary layer. This aquifer has a good yield and is commonly used for drinking water supply. The flow in the Quaternary aquifer is horizontal following one direction. The underlying Buntsandstein aquifer is separated from the Quaternary aquifer by an aquitard but locally connected to the upper aquifer through faults and other discontinuities. The Buntsandstein is heterogeneous with considerably smaller flow rates and yields are than in the upper aquifer. The water quality in the Buntsandstein aquifer is generally poorer than in the Quaternary layer primarily due to in parts high salinity. Water from the sandstone aquifer is only occasionally used for drinking water supply. Further below, between the aquifers and the ore deposit, is an aquiclude, consisting of very heterogeneous material. Stratigraphically, the aquiclude is formed by Aller, Leine, and various Zechstein layers and groundwater movement through it is virtually non-existent.

4.4. Biota

The biota consists of the flora and fauna typical for the temperate broadleaf and mixed forest – ecoregion. Oaks (Quercus spp.), maples (Acer spp.), beeches (Fagus spp.) and birches (Betula spp.) are the most common trees, but different conifers are also common. Smaller trees, saplings, shrubs and bushes along with dense undergrowth can also be observed. The highest amount of biodiversity is observed near the ground surface. To simplify the EIA, the site is expected to reside solely on a single ecoregion, and not contain for example bogs, that are relatively common near the reference area\textsuperscript{2}, or montane areas typical for southern Germany. Further, it is also expected that there are no nature protection areas or endangered species residing near the site.

4.5. Built environments and inhabitants

The EIA area is hilly country with sections of forest and agricultural fields in the lower lying areas. There is a zone of elongated lakes in a forested setting extending across the area in an arc-like formation. Rivers mostly run S-N in the area. Small towns are located either within the agricultural landscape or in the forested sections. There are also farmhouses outside the small towns in the rural areas. Several large cities also exist in the area with an industrial job base. The long human presence has resulted in several sites of cultural and historical significance that may affect the project design and siting.
There are almost seven million people living in the larger project area, four million in Saxony and almost three million in Lower Silesia in Poland. According to Statistisches Bundesamt Deutschland’s Regionalatlas, the population density in the eastern part of Saxony was between 123.1 (Görlitz) and 127.8 inhabitants per km² (Bautzen) with a declining population (-7.2 - -9.7 /a/10 000 inhabitants) in 2015. In the neighbouring Polish vojvodship (a NUTS 2 region) of Dolnoslaskie (Lower Silesia), two million of the 2.9 million inhabitants live in urban areas according to the Central Statistical Office of Poland. The population density is 145.6 inhabitants/km² in this 19 947 km² vojvodship. However, there are large forested areas and extensive nature conservancies on both sides of the border in the project area. In any case, it is likely that there will be permanent residents nearby the project site making exposure to noise, visual pollution, vibrations, traffic effects etc. possible.

Copper appears to have been extracted from the rich and widespread Kupferschiefer -formation already since the Bronze Age. Large portions of the resource have already been exhausted completely, in particular in the Mansfeld and Sangerhausen districts of Germany (Borg et al., 2012). The formation continues to be utilised by several Polish underground copper mines and exploration projects are ongoing.

The long history of mining in the region means that signs of previous mining operations at the project site are obvious. For example, only a kilometre south from Weißwasser, a lignite mine is being operated by Lausitz Energie Bergbau AG. These mining activities also involve local lowering of the water levels in the shallow aquifers (Wolkersdorfer and Thiem, 1999). Generally, the area of Central Europe is densely populated and thus conflicts with existing infrastructure will be unavoidable.

Widespread interaction, open communication, and forming good public relations with the local resident is crucial. Previous mining operations could have impacted the stance of the inhabitants towards future projects and could thus affect the process of getting a Social Licence to Operate (SLO). People might have both positive (e.g. the hope of the project acting as a source of new jobs, services, infrastructure, etc.) and/or negative (e.g. fear of environmental impacts) thoughts about the new project, see e.g. Jartti et al. (2014) and Suopajärvi et al. (2016) who studied people’s opinions of the Finnish mining sector. Some part of population might also feel sceptical towards the production method, because the use of hydraulic fracturing in oil and gas industry has roused a large intercontinental debate leading to multiple documentaries and even movies over the method’s possible negative environmental and health impacts.
5. EIA - Site appraisal and construction phase

Before the mining operations, the existing resource and its suitability for the ISR method need to be thoroughly assessed. Both geological and hydrogeological properties of the potential production site must be well understood for the mine to operate both efficiently and sustainably.

Baseline studies on the subsoil properties can be made with soil sampling followed by geochemical analyses and with environmental geophysics including methods such as ground penetrating radar, resistivity measurements and refraction seismic surveys. Environmental impacts from these non-intrusive methods are usually minor and the equipment can be handled by a small group of people (less than five) moving either by foot, all-terrain vehicles or cars (via regular roads). The impacts are largely limited to trampling down vegetation and emissions from the possible vehicles. In refraction seismic surveys, small explosive charges are sometimes used to produce the seismic signal as explosives provide a strong, sharp signal with good depth penetration. The use of explosives might induce nitrogen emissions, noise and ground vibrations on top of the previously mentioned influences.

Based on the geophysical and geochemical studies, core drilling is used to delineate the inferred mineral resource, and to estimate groundwater flow patterns and the chemical quality of the water. It is also important to gather information about the pre-mining, natural conditions at the subsoil as this information is vital to later detect mining-fluid excursions outside the ore zone during the ISR operation, and to observe aquifer restoration performance as the restoration proceeds. The biggest environmental impacts during this stage are produced during the drilling phase, which includes, for example, handling of drilling mud, drill cuttings and noise. Environmental impacts of the drilling are discussed in more detail in Chapter 6. Environmental impacts from downhole geophysics can be expected to be small.

Due to the nature of the ISR production method, hydrogeological settings at the production site must be known in detail. Hydraulic properties of the host rock affect the performance of fracking and leaching processes, and discontinuities such as cracks and faults might act as unwanted groundwater flow paths through which the mining fluid can migrate.

Hydrogeological properties of the subsoil can be estimated with methods such as packer tests or pumping tests. Slug tests could be used in the preliminary stages of the study, but focus should be on tests yielding more detailed results.

Packer tests can be used to analyse hydraulic conductivity along a drill hole by dividing the hole into sections, isolated by inflatable packers. Vital information such as vertical variation in hydraulic conductivity, can then be analysed. The most significant environmental impacts related to the actual tests (drilling impacts excluded) are caused by the use of a generator to produce electricity for a water pump (e.g. COx, airborne particles, noise and risk of fuel spillages), possibly harmful quality of the pumped water (due to, for example, high salinity) and impacts related to moving the...
equipment and personnel on and off the test site. Still, overall the impacts can be considered small, especially as the duration of the test is limited to usually few days at most.

Pumping tests aim at investigating the permeability of a rock domain. In the test the aquifer is stressed by pumping water out from a test well while simultaneously the water levels in one or more surrounding observation wells as well as in the test well itself are being monitored. The test is slow to conduct (testing can last anywhere from hours to even months). Pumping tests also cause increased environmental impacts compared to the packer tests as the pumping, requiring electricity which at a rural site might have to be produced with a gas or diesel generator operated for extended time periods (Kinnunen, 2005). Also, the water from the test well needs to be continuously discarded into a source of constant head (e.g. a lake or a river) to prevent the pumped water from entering back in to the groundwater system. In worst case scenario, this might mean transporting the water off-site with tank trucks and treating the water (e.g. due to high natural salinity) before releasing it into a surface water system.

Along with the hydraulic tests, water samples should be collected and analysed to form a hydrogeochemical baseline. Different tracer tests (using non-reactive tracers such as distilled water or tritium isotopes) could be further used to map out natural hydraulic connections between different observation wells.
6. EIA - Wellfield construction and stimulation phase

6.1. Wellfield construction

6.1.1. Spatial and visual footprints

Spatial footprint is a measure of the land surface and the supported biota that is disturbed by the activity. The spatial footprint of the drilling phase consists of the drilling pads required to drill the injection and collection well pairs and the monitoring wells, any auxiliary facilities such as drill mud pools if they are located outside the drill pad area, and access or maintenance roads.

Clancy et al. (2017) studied the physical footprints of shale gas and oil well pads in the UK, The Netherlands, and Poland. In addition, they used examples from the US, where many more wells have been drilled, to estimate the likely physical footprint of well pads for shale gas development in Europe. There is considerable variation in the average footprints between the countries: 1.08 ha in the UK, 5.38 ha in The Netherlands, and 0.29 ha in Poland. When the number of wells per site is considered, the corresponding footprints are 541, 6370, and 2870 m²/well.

Based on the data in Clancy et al. (2017), a reasonable footprint for a well pad with 20 wells can be set to approximately 10,000 m² if special attention is paid to making the pads as compact as possible. These drill pads include all structures needed in the drilling phase, such as noise barriers, but no other production facilities other than those needed for pumping. Based on Clancy et al. (2017), an estimated 250 m of access road comes with each well pad (~830 m²). In this scenario, all other infrastructure is located outside the well pad.

The visual footprint of a drilling rig when it is in operation is considerable because it includes a tall derrick for handling the drilling pipes. However, the derrick is not very large in diameter and it is only visible during the drilling phase. During the production phase, the structures on the well pad are of low profile.

6.1.2. Noise emissions

Behrens and Associates Inc. (2006) analysed noise impacts and noise mitigation in gas well drilling. They found that average drilling sound levels at 60 m from the drill rigs was between 70-80 dBA. Unmitigated drill rig brake noise was audible up to 300 m from the rig. Highest noise levels were measured in the casing phase (~100 dBA at the rig). However, drilling noise mitigation systems reduced the noise levels considerably (brake noise control, acoustical blankets, engine mufflers, temporary sound control walls). Therefore, sound level increases of 5 dBA at 60 m are expected with proper installation and operation of noise control methods.
A smaller increase in long term average noise levels was reported in the modelling study of roadside noise related to well pads by Goodman et al. (2016). The authors studied traffic impacts for well drilling and fracking operations for a six well pad under two different scenarios (low and high, based on truck visits required in different phases of the operation). When reported as long-term average $L_{Aeq}$ values as required for noise mapping in the EU Noise Directive, the contribution of fracking operations over the operating period are minuscule with increases less than 1 dBA. However, certain phases of the operation may cause more roadside noise. In addition, it is essential to devise a vehicle arrival and departure policy that restricts the movements to times of the day when they cause the least harm and increase over background levels. In addition, traffic can be directed to road types where the relative increase is not critical.

6.1.3. Traffic effects

Goodman et al. (2016) present a traffic impacts modelling (TIM) study of a six-well hydraulic fracturing well pad operation from start to completion. The model includes a traffic demand model for the different stages of the drilling and stimulation operation (numbers of truck visits), a traffic assignment model that looks at how the required traffic is distributed in space and time, the impacts model that estimates the emissions based on the above considerations, and a post processing module to compare the emissions to baseline traffic conditions on different road types and times of day. The paper considers two scenarios (‘low’ and ‘high’) based on water and proppant demand and flowback water.

The results of the modelling are summarised in Table 2. The years in the table represent expected developments in vehicular emissions control methods that is expected to influence the NOx/NO2 ratio in particular. The results have been normalised to represent emissions per a single well. In the table $uCO2 = $ total mass of CO2 after all exhaust components of fuel exhaust have oxidised; $pNO2 = $ emissions of NO2 directly from the vehicle tailpipe, i.e. prior to the additional photochemical generation of NO2; PM10 and PM2.5 = particulate matter of <10 µm and <2.5 µm respectively; $L_{Aeq} = $ sound power converted to equivalent roadside noise level; ESAL = equivalent standard axle loads. The ‘low’ and ‘high’ scenarios are based on truck visits (685 vs 1050) required by different amounts of water, proppant, and flowback water.
Table 2 Traffic emissions from a six-well well pad operation, normalised to emissions per a single well.

<table>
<thead>
<tr>
<th>Starting year</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2010</th>
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<th>2020</th>
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<tr>
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<td></td>
</tr>
<tr>
<td>uCO2</td>
<td>35.1–38.8</td>
<td>34.9–38.3</td>
<td>34.6–38.2</td>
<td>53.4–58.9</td>
<td>52.6–58.1</td>
<td>52.5–58.0</td>
<td>t/well</td>
</tr>
<tr>
<td>NOx</td>
<td>171–253</td>
<td>54.4–111.2</td>
<td>11.9–21.3</td>
<td>261–385</td>
<td>83.3–170</td>
<td>18.3–44.0</td>
<td>kg/well</td>
</tr>
<tr>
<td>pNO2</td>
<td>22.7–32.6</td>
<td>6.3–12.2</td>
<td>1.2–2.9</td>
<td>34.7–49.6</td>
<td>9.6–18.7</td>
<td>1.9–4.5</td>
<td>kg/well</td>
</tr>
<tr>
<td>PM10</td>
<td>6.4–8.7</td>
<td>4.1–6.5</td>
<td>3.4–5.9</td>
<td>9.8–13.2</td>
<td>6.3–10.0</td>
<td>5.2–9.0</td>
<td>kg/well</td>
</tr>
<tr>
<td>PM2.5</td>
<td>4.9–5.9</td>
<td>2.8–3.9</td>
<td>2.1–3.3</td>
<td>7.5–9.0</td>
<td>4.1–5.9</td>
<td>3.2–4.9</td>
<td>kg/well</td>
</tr>
<tr>
<td>HC</td>
<td>5.6–6.6</td>
<td>1.0–1.2</td>
<td>0.3–0.4</td>
<td>8.5–10.1</td>
<td>1.6–1.9</td>
<td>0.4–0.5</td>
<td>kg/well</td>
</tr>
<tr>
<td>LAeq</td>
<td>0–0.15</td>
<td>0–0.15</td>
<td>0–0.15</td>
<td>0.01–0.20</td>
<td>0.01–0.20</td>
<td>0.01–0.20</td>
<td>dBA</td>
</tr>
<tr>
<td>ESAL</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>7.4</td>
<td>7.4</td>
<td>7.4</td>
<td>×1000 axles/well</td>
</tr>
</tbody>
</table>

6.1.4. Drilling waste

Drilling waste consists of drill cuttings and the drilling fluid that brings the cuttings from the wellbore. The drill cuttings represent the natural rock types that the drill hole has intersected. Once surfaced, the drill mud is treated to separate the cuttings from the rest of the drill mud in a solids separation system typically consisting of ‘shale shakers’, a mud tank (‘pit’), a solids dryer, and other solids separators. After the removal of the solids, the rest of the drilling mud can be taken back to circulation if it still meets the specifications. The possibilities of drill mud (fluid) reuse thus depend on both the treatment (cleaning) process and the requirements for the recirculated fluid.

Drilling waste volumes of 0.5 m³ per metre drilled are expected (AMEC, 2009; ESRF, 2004). This is a conservative estimate used in the impact assessment. It is estimated that 70 % of the drilling waste consists of solid material (cuttings) and 30 % is liquid wastes.

Depending on the waste disposal method and the waste composition, the waste might need to be treated before final disposal. Common treatment steps include for example solidification and stabilisation. Solidification refers to encapsulating the wastes with a less reactive surface material. This limits contaminant migration by decreasing the area of the exposed waste surface. In stabilisation, the chemical composition of the wastes is altered into less soluble, less reactive and less harmful forms. Historically, in oil and gas industry, for example fly ash, cement, lime and calcium oxide have been used for drill mud solidification and stabilisation (Aird, 2008). Also, water might need to be removed (in case of e.g. pit burial) or added (e.g. slurry injections) to the wastes depending on the waste disposal method.

Safety wise, the best option for final disposal would likely be to transport the waste material off the site and discard it through contaminated soil recycling or landfills. However, such an approach might prove to be too expensive especially if the material cannot be effectively re-used for new purposes.
Slurry injection is a common method to deal with drilling fluids and other liquid wastes especially in oil and gas industry, where in some cases even dedicated waste injection wells are used (Veil and Dusseault, 2005). In the shale oil and gas industry the problem with induced seismicity has been identified to be closely related to waste water reinjection, see further Section 6.2.2. According to a Slurry injection database by Veil and Dusseault (2003), many drill site operators reported annual savings up to hundreds of thousands of dollars while injecting wastes compared to soil recycling or landfills. In the case of ISR slurry injection may not be an optimal choice due to the risk of interference with the ongoing ISR operation.

Another possible waste disposal method is pit burial, which is the most commonly used method with onshore oil and gas industry drilling wastes (Aird, 2008). Operators often find pit burial to be tempting due to it being a low-cost, low-technology method where the wastes can also be disposed onsite. However, the method can only be considered viable if the wastes after treatment steps have sufficiently low concentrations of biologically available harmful substances. Concentrations of harmful substances can, in some cases, be diluted below regulation limits by mixing the wastes with clean soil material (Bansal and Sugiarto, 1999). It should be noted that European legislation prohibits dilution of hazardous waste with the objective to lower the content of hazardous substances below the thresholds for defining it as non-hazardous waste (EC, 2008).

Wastes should be dug below the major rooting zone of plants, but above the water table. Locations with naturally low permeability soils, such as clays, should be preferred. Contamination risk can be further limited by use of liners and low permeability materials during pit construction. Slope integrity of the pits should also be considered from an engineering viewpoint. Sites with high permeability soils, hillsides and sites near surface water bodies should be avoided. At drilling sites, an approach of multiple smaller pits close to the drilling site has been found to be preferable as it makes the risk and scale of possible spillages smaller (Aird, 2008). However, this also spreads the wastes into a larger area. Bansal and Sugiarto (1999) estimated the costs of pit burial to be roughly 5€ per 100 l of waste.

The combination of both slurry injection and pit burial could be one solution to the waste disposal problem. Here, the more liquid wastes and waste waters from pit drying would be discarded through injections, whilst the remaining solids would be discarded through pit burial. This combination could lead to injections with higher water content, and so also lower viscosity, making them less prone to further fracturing and well clogging. At the same, the pit evaporation process would become more efficient as part of the water could be removed via the injection process. Similar combination of evaporation ponds and deep injection wells is also quite commonly used in uranium ISR operations (NRC, 2009).
6.1.5. Spillage during drilling

The drilling fluid consists mostly of a bentonite water sludge with additives (e.g. sodium salt of carboxymethyl cellulose, caustic soda, detergent and skimmer). The drilling fluid utilised during the preparation of the well field will be circulated in a closed circuit. Spill of drilling fluid can occur in emergency situations, e.g. pipe breaks or blockage. In addition to drilling fluid, hydraulic oils and lubricants are handled at the drilling site.

Leakage prevention and mitigation of potential effects of leakages are important issues in the design of the drilling site.

6.1.6. Exhaust emissions from stationary sources

Exhaust emissions from a diesel-electric drill rig not operating on mains power is estimated based on the generator sets meeting, but not exceeding, the strictest emissions standards in force at present. These are given in Table 3 and Table 4.

Caterpillar 3512 and its variants are the most modern, yet common power modules for drilling operations using electric AC rigs. The emissions can be estimated based on the newest variety, the CAT 3512E land drilling power module which meets the US EPA Nonroad Tier 4 emission standards. It is assumed that two units are present and they operate at an average power output of 1700 kW during the drilling phase. Based on 24 h operation and US Tier 4 emission standards this results in 142.8 kg CO₂, 7.75 kg NMHC, 27.3 kg NOx, and 1.22 kg PM emissions during a 24 h operating period.


<table>
<thead>
<tr>
<th>Year</th>
<th>Category</th>
<th>CO</th>
<th>NMHC</th>
<th>NOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Generator sets &gt; 900 kW</td>
<td>3.5 (2.6)</td>
<td>0.40 (0.30)</td>
<td>0.67 (0.50)</td>
<td>0.10 (0.075)</td>
</tr>
<tr>
<td></td>
<td>All engines except gensets &gt; 900 kW</td>
<td>3.5 (2.6)</td>
<td>0.40 (0.30)</td>
<td>3.5 (2.6)</td>
<td>0.10 (0.075)</td>
</tr>
<tr>
<td>2015</td>
<td>Generator sets</td>
<td>3.5 (2.6)</td>
<td>0.19 (0.14)</td>
<td>0.67 (0.50)</td>
<td>0.03 (0.022)</td>
</tr>
<tr>
<td></td>
<td>All engines except gensets</td>
<td>3.5 (2.6)</td>
<td>0.19 (0.14)</td>
<td>3.5 (2.6)</td>
<td>0.04 (0.03)</td>
</tr>
</tbody>
</table>

Table 4 European Stage V emission standards for generator set engines above 560 kW (NRG).

<table>
<thead>
<tr>
<th>Category</th>
<th>Ign.</th>
<th>Net Power kW</th>
<th>Date</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>PM</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRG-v/e-1</td>
<td>All</td>
<td>P &gt; 560</td>
<td>2019</td>
<td>3.50</td>
<td>0.19a</td>
<td>0.67</td>
<td>0.035</td>
<td>-</td>
</tr>
</tbody>
</table>
6.2. Stimulation

6.2.1. Direct effects of the fracking operation

It has been assumed here that water with sand added as proppant will be the only fluid used in the hydraulic fracturing. Therefore, the environmental effects of the fracking fluid itself have been judged to be small. Indirect effects like induced seismicity are treated below.

6.2.2. Seismic effects

Multi-stage hydraulic fracturing along the horizontal wellbores has been considered to be an optimal solution for the BIOMOre stimulated in-situ leaching (Weber and Yildizdag, 2017). It is well known that fracking fluid injection might induce micro seismic events (see e.g. Rutledge and Phillips, 2003; Warpinski et al., 2004). The magnitudes of such induced earthquakes were given by Davies et al. (2013) as a range of 1 – 3.8. The earthquake with the highest magnitude (3.8) was recorded in the Horn River Basin, Canada. Such ground motions during and after the hydraulic fracturing are normally related to reactivation of faults (e.g. Cipolla et al., 2012; Maxwell et al., 2008; Vulgamore et al., 2007; Warpinski et al., 1998; Wolhart et al., 2006). During hydraulic fracturing in shale gas reservoirs, the main deformation mechanism is assumed to be shear reactivation of natural fractures and fault planes (Zoback et al. 2012). Figure 12 summarises the cases of fault reactivation due to flow of a fluid in a low-permeability reservoir with an intersecting fault (Davies et al., 2013). Potential mechanisms are enumerated by the author on that figure as follows:

1. Direct connection and injection into the fault,
2. Fluid flow through the stimulated hydraulic fractures into the fault,
3. Fluid flow through the existing fractures,
4. Fluid flow through permeable strata and along bedding planes.

The experiences from hydraulic fracking in conjunction with extraction of shale oil and shale gas is that fracking and injection of excess water into deep aquifers tend to induce micro seismic movements. Detecting seismic effects by water injection during a stimulation is of great importance for avoiding damage on the earth surface and possible leakage into surface aquifers.

Relatively small perturbations of the pore pressure have been shown to trigger seismicity, even in tectonically stable areas. For example, in Oklahoma, pore pressure increases of less than 1 MPa have triggered earthquakes 10 km away in basement within weeks (Keranen et al., 2014).

In-situ stress state was computed at the North Sudetic Trough prior to fracturing to determine the mechanical conditions. The background seismicity in this area is low. Several models and simulations were used to assess the risk for reactivation of faults.
in conjunction with hydraulic fracturing. The CAD software RHINO (Version 4) and the finite element code 3DEC (ITASCA, Version 5.2) were used to define the geologic setting and to simulate in-situ stress state respectively (Weber and Yildizdag, 2017).

Figure 12 Illustration of potential fault reactivation mechanisms in a low-permeability reservoir (after Davies et al., 2013). $P_f$ is the pore pressure of fluid through a fault and $\sigma_N$ is the normal stress along the fault.

Figure 13 A 3D CAD model showing the model domain (left side) and proposed wellbore configuration together with the geological setting beneath the selected drilling site (right side). The figure includes maximum earthquake magnitudes observed in the near vicinity of the drilling site adapted from the human induced earthquakes database (Foulger et al., 2017; Wilson et al. 2017). The green and blue circles centred at the assumed drilling site indicate an epicentre criterion (Davis and Frohlich, 1993) and the maximum influence area of a stimulation, respectively. The ratio for analysing possible fault reactivations is called “slip tendency” and is calculated along weakness surfaces (i.e. faults) in the 3D numerical stress model of the North Sudetic Trough, see Figure 14. The slip tendency ($T_s$, [-]) is based on Amonton’s Law and it is an indicator of slipping that is mathematically expressed by Equation 1:

$$T_s = \frac{\tau}{\sigma_n'}$$

$\tau$ Shear stress on a weakness plane [MPa]
$\sigma_n'$ Effective normal stress on a weakness plane [MPa]
Figure 13 A 3D CAD model showing the model domain (left side) and proposed wellbore configuration together with the geological setting beneath the selected drilling site (right side).
A slip along a fault is expected to occur when the slip tendency is equal to or greater than one. The computed slip tendency along faults are shown in Figure 14 together with pictograms of the assigned tectonic stress regime. The computed maximum value is not greater than 0.5 indicating that slipping is not expected to occur with assumed conceptual model and model parameters. It should be noted that the computed slip tendency depends mainly on the stress field, the orientation of the faults and their mechanical parameters.

These results are based on the fact that no fault was detected within the maximum influence area of the selected drilling site, see Figure 13. However, previously undetected faults can be revealed by induced seismicity during the stimulation. It is recommended the stimulation is monitored with instruments such as geophone strings to assess underground motions during and after the stimulation. It is foreseen that the fracturing fluid would be a mixture of water and well-sorted sand. The influence of sand particles on the mechanical properties of undetected faults and hence the risk for triggering seismic events is still open.

**Figure 14** Calculated slip tendency values [-] and failure zones along faults in the numerical model together with inset pictogram showing assigned tectonic stress regime.
6.2.3. Destruction of cap rock by uncontrolled fracture generation

To enhance productivity of the underground target zone and to fulfil high environmental safety standards, a modelling-based optimisation is normally required in hydraulic fracturing operations. The environmental risk assessment performed within the BIOMOre includes assessment of the risk for fracture transition from the target ore zone (Rotliegend – sandstone) into the overlying barrier rock (Zechstein – limestone). Hydraulic fracture simulations and optimisations performed in the project do not show any critical fracture transitions. Nonetheless, this is a risk which should be carefully investigated.

Weber and Yildizdag (2017) mean that the limestone horizon could act as a stress barrier causing the extension of hydraulically induced fractures to be restricted to the Rotliegend sandstone leaving the Zechstein limestone effectively intact. To estimate the risk of fracture transition from sandstone into limestone, additional simulations were performed.

Simonson et al. (1978) investigated fracture transition into barrier rock driven by stress field changes. An artificial fracture propagates into a barrier if 1) the fracture is in direct contact with the barrier rock boundary and 2) the critical fracture pressure $p_{\text{frac}}$ at this boundary is overcome by the fluid pressure induced due to hydraulic fracturing (continuum mechanical approach). If these two aspects are fulfilled there is a potential for fracture transition into the barrier rock. The critical fracture pressure is given in Equation 2:

$$p_{\text{frac}} = \sigma_3 + \sigma_T \quad (2)$$

In the Equation, $\sigma_3$ is the smallest principal stress and $\sigma_T$ is the tensile strength of the rock by assuming positive signs for compressive stresses. The critical fracture pressure in the Zechstein - limestone at 1500 m depth is estimated to be 46.55 MPa. A decrease of one of these parameters ($\sigma_3, \sigma_T$) reduces the critical fracture pressure. Since the barrier is intact in the optimisation simulations, the parameter $p_{\text{frac}}$ in the limestone layer must be artificially reduced to obtain such lower critical pressures that would result in fracture transition. Therefore, the horizontal stresses ($\sigma_1, \sigma_3$) where reduced in different simulations such that the critical fracture pressure was reduced by $\Delta p_{\text{frac}} = 15, 20, 25$ and $30 \%$.

In the optimisation simulations, an injection time of 68 s with an injection rate of $5 \cdot 10^{-2}$ m$^3$/s was used. For the fracture transition simulation, the injection time was increased to 80 s to increase the injected volume. A bigger volume generates larger fractures thus increasing the potential for fracture transition.

Figure 15 show the fracture pattern for the simulation cases with $\Delta p_{\text{frac}} = 15, 20, 25$ and $30 \%$. If the critical fracture pressure of the barrier rock is reduced by 15 % (Figure 15a) no transition occur and the fracture is contained in the sandstone layer. For a reduction by 20 % (Figure 15b) transition is possible and the fracture breaks through the limestone boundary. The fractured area in the sandstone then becomes smaller. If the critical fracture pressure decreases more (Figure 15c, d), the fracture lengths within the limestone layer increase and the fracture area within the sandstone becomes even smaller.
Figure 16 and Table 5 show the increase in fracture length when decreasing the critical fracture pressure. If the critical fracture pressure of the barrier rock is small enough a sudden and rapid increase in fracture length occur. The fracture then propagates in the Zechstein – limestone as a consequence of less mechanical resistance.

The simulations show that a decrease of $\Delta p_{\text{frac}}$ of 20 % is necessary to generate propagation of hydraulically induced fractures into the barrier rock. For this case the critical fracture pressure is 37.24 MPa and therefore 9.31 MPa smaller than the value estimated by Weber and Yildizdag (2017).

Simulations show that there is a possible risk of fracture transition into the barrier rock when the critical fracture pressure is reduced by about 20 %. However, a reduction of critical fracture pressure within the barrier occur preferably in areas where the barrier’s stress field is disturbed (stress drop in $\sigma_3$), the barrier is damaged ($\sigma_T$, barrier is nearly zero) and/or it’s values of geomechanical parameters are highly scattered. Therefore, it should be ensured that the wellbore site is in areas with nearly undisturbed stress field (e.g. no main faults near to the site) and intact barrier rocks. Stress field measurements and experimental tests should be conducted in order to estimate underground conditions of the barrier. Nonetheless, state of the art monitoring techniques must be used during the stimulation process to avoid critical fracture propagation.

Table 5: Values for the depth of upper fracture tip and lower limestone boundary as well as fracture length within the barrier rock.

<table>
<thead>
<tr>
<th>$\Delta p_{\text{frac}}$ [%]</th>
<th>Depth of upper fracture tip [m b.s.l.]</th>
<th>Depth of lower limestone boundary [m b.s.l.]</th>
<th>Fracture transition [yes/no]</th>
<th>Fracture length within limestone [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>-1528</td>
<td>-1532</td>
<td>yes</td>
<td>70</td>
</tr>
<tr>
<td>25</td>
<td>-1528</td>
<td>-1532</td>
<td>yes</td>
<td>62</td>
</tr>
<tr>
<td>20</td>
<td>-1528</td>
<td>-1532</td>
<td>yes</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>-1532</td>
<td>-1532</td>
<td>no</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>-1532</td>
<td>-1532</td>
<td>no</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 15: Fracture pattern for the simulation cases a) $\Delta p_{\text{frac}} = 15\%$, b) $\Delta p_{\text{frac}} = 20\%$, c) $\Delta p_{\text{frac}} = 25\%$ and d) $\Delta p_{\text{frac}} = 30\%$.

Figure 16: Fracture length within the limestone layer for the simulation cases $\Delta p_{\text{frac}} = 15, 20, 25$ and $30$. 
6.2.4. Uplift and subsidence of the overburden

Mining and production of underground resources causes ground subsidence as well as other related movements and deformations. The results can be hazardous and induce damages of surface and subsurface infrastructure with negative impact on the environment and on the efficiency of the production process.

For ground control, subsidence measurements, subsidence prediction and damage mitigation strategies are essential parts of the hazard and production management. To maximise quality and accuracy of this information an integration of all available datasets is necessary. A suitable subsidence model and integration methodology offers stochastic subsidence modelling with subsidence prediction and parameter estimation based on in-situ measurements.

The integration result is a 3D dynamic movement and deformation model that allows calculating all relevant deformation components on and below the surface. In consideration of temporal and spatial changes of the reservoir due to production over time, it enables prediction of intermediate and future deformation.

The proposed method is an important element of production planning for the bioleaching method and a comprehensive tool for hazard mitigation and assessment.

Due to the ground and strata movements caused by underground resources production, the surface is affected in various different ways. In addition to impair or damage to buildings, such as residential houses, industrial plants or of transport infrastructure also undesirable changes in the hydrology (water stream disorders and changes in the water pipe grades) occur on the surface. The induced strata deformations present a severe hazard to production and injection borings and integrated equipment underground. Finally, also the general landscape is altered by subsidence.

The size and type of ground movement can be described in detail with the subsidence model introduced in the next chapters. The model is based on the stochastic approach by Knothe (1953) including the parametrisation according to the Ruhrkohle method according to Ehrhardt and Sauer (1961). Further model adjustments and improvements towards application for oil and gas reservoirs were integrated by Hejmanowski (1993), Hejmanowski et al. (2001), Sroka and Wittkopf (1992), Sroka and Hejmanowski (2006), and Sroka and Tajduś (2009).

The model incorporates underground structural features, production data, geologic information and in situ measurement data to predict temporal and spatial dense ground movement information. The modelling concept of data integration presents a powerful link between the characteristics of the deposit, production and observed movements which results in a complete three-dimensional description of surface and strata movements and deformations at any point in time. Below the modelling approach is demonstrated and illustrated for an example deposit - Zimmermann (2010; 2011).

The applicability of this method specifically for bioleaching and the necessary modifications are subject to investigation and analysis in the project.
Based on the subsidence model hazardous and damaging effects can be predicted and assessed for wide areas on the surface. Basis of the assessment are classification method of surface objects with regard to their sensitivity to induced movements. Studies of Budryk and Knothe (1956), Ledwon (1987) and Pohl (2002) summarise suitable, easy to apply criteria that allow a large-scale assessment of subsidence areas. For each sensitivity class specific limit values (tilt, curvature, extension/compression) for maximum allowed object stress are defined, which are not to exceed for the effective protection of the objects. However, especially in case of complex objects, such as industrial plants, drillings or underground workings, specific studies are still necessary to assess the individual sensitivity to deformations.

a) Modelling of ground and strata movements

The general and primary cause for subsidence and ground deformation is the loss of material volume in the underground related to mining and production. As a consequence, the collapse and compaction of subsurface cavities lead to rock mass deformation and surface subsidence. Below this movement process and the corresponding modelling is described specifically for the case of oil and gas production. The approach can be modified towards specific needs of bioleaching.

In case of oil and gas production the general cause for subsidence is a decrease of reservoir volume due to lowering pore pressure and increasing compaction of the carrier rock – Hejmanowski (1993). The compaction can be described both spatially and temporally with the model described. Using the initial movements related to the compaction subsequent deformations within the strata and movements of the surface are calculated using a stochastic transfer function.

The model-based description of carrier rock compaction is centred on reservoir elements defined by location, volume, porosity and pressure state. Figure 17 shows an illustration of the reservoir elements (left) and an example reservoir with colour coded elements representing the depth distribution.

![Figure 17: Schematic presentation of field discretisation by reservoir elements (left, according to Hejmanowski (1993)) and example discretisation of the depth of the reservoir (right)](image)

The height change of each element $\Delta M(t)$ due to its compaction (see Figure 18) is calculated with equation (3):
\[ \Delta M(t) = c_M \cdot [p_0 - p(t)] \cdot M_0 \]  
\hspace{1cm} (3) 

with:  
\[ c_M \] - coefficient of compaction  
\[ p_0 \] - initial pore pressure at time \( t_0 \)  
\[ p(t) \] - pore pressure at prediction time \( t(t \geq t_0) \)  
\[ M_0 \] - height of the reservoir element

Further developing equation (3) the compaction volume \( \Delta K(t) \) is given by equation (4): 
\[ \Delta K(t) = \Delta M(t) \cdot L^2 \]  
\hspace{1cm} (4) 

with:  
\[ L \] - edge length of quadratic element

The coefficient of compaction characterises the deformability of the carrier rock and can be determined by in-situ rock tests for example. According to Teew (1973) \( c_M \) is related to the carrier rock porosity (see Figure 18, right). Using this relation \( c_M \) can also be derived by the commonly known distribution of porosity within the reservoir.

Figure 18: Compaction of a reservoir element (left, according to Hejmanowski (1993) and Sroka and Tajduś (2009)) and relation between carrier rock porosity and compaction (right, according to Sroka and Wittkopf (1992) and Zimmermann (2011))

To calculate subsidence \( \Delta S \) the element compaction is multiplied with the stochastic transfer function \( \varphi(R(z), d) \) and the subsidence factor \( a \). The subsidence factor takes the bulking of the overlaying strata into account. The transfer function is based on the Gaussian influence theory by Knothe and parametrised according to the Ruhrkohle method and is not described in further detail at this point.

Figure 19 (right) shows a 3D visualisation of the calculated subsidence distribution inside rock mass and on the surface. Besides subsidence all further movement values
which are especially relevant for hazard and influence estimation and mitigation such as slope, curvature, displacement and strains can be derived and calculated [6].

![Figure 19: Transfer of element compaction to the surface (left, according to Hejmanowski et al. (2001)) and 3D visualisation of calculated subsidence inside rock mass and on surface (right)](image)

**b) Model adjustments and calibration**

The determination of an optimised set of model parameters is conducted by incorporating *in-situ* subsidence measurements in conjunction with a least squares adjustment using the Gauß-Markov method (Hößelbarth and Sroka, 2007). The necessary mathematical relation between parameters and measurement observations is given by equation (5). Basis for parameter estimation in this case is the measured subsidence at a given calculation point $s_j$.

$$s_j(t) + v_j = a \cdot \Delta K(t, c_M) \cdot \varphi(y)$$  \hfill (5)

with:

- $v_j$ - correction values of subsidence
- $a, c_{Mj}, \varphi(y)$ - parameter values to be optimised

An illustration of the data integration and subsidence modelling is presented in Figure 20. Existing spatially sparse distributed measurement points (e.g. INSAR/GPS) are used for model calibration. The resulting modelling output delivers a dense pattern with information about subsidence and other important ground movement elements. Furthermore using the time-varying reservoir pressure a forecast of future ground movements or between measurement epochs is possible.
c) Movement impact evaluation

The size and type of ground movement can be described in detail with the elements introduced in the previous chapters. It is however difficult to estimate the actual damage effect of movements on specific objects. Reasons for this are the diverse types of objects with different design, size and foundation and their different sensitivity to the individual elements of ground movement.

To gain knowledge about the relation between mining induced ground movements and corresponding object damages many investigations were conducted on this topic in the past in Europe, for example by Budryk and Knothe (1956), Ledwon (1987) and Pohl (2002). Aim of these investigations was to find suitable, easy to apply criteria that allow a large-scale assessment of mining areas in densely populated Europe. Basis of the assessment methods is therefore a general classification of surface objects with regard to their sensitivity to mining induced movements. For each sensitivity class specific limit values (tilt, curvature, extension/compression) for maximum allowed object stress are defined, which are not to exceed for the effective protection of the objects. However, especially in case of complex objects, such as industrial plants or bridges, specific studies are still necessary to assess the individual sensitivity of the object.

In the following, important findings and conclusions of previous studies on the damage effect of mining induced ground movements, in particular from the European longwall mining, are summarised.

The pattern of mining damages depends, in addition to the common ground movement, on the specific, design-related features of the affected object. Each object has a different damage sensitivity regarding the various elements of ground movement. Table 6 shows that rail tracks or bridges are relatively sensitive to subsidence, which has a strongly negative effect on their location relative to the connected infrastructure. Row houses are more endangered by tilt and extension/compression which deteriorate the quality of life or cause damage to the
building themselves. Detailed explanations which describe the influence of different
ground movements to different objects, can be found e.g. in Kratzsch (2008).

Table 6: Influence of separate ground movement elements on surface objects (x - medium
sensitivity, xx - high sensitivity) after Kratzsch (2008)

<table>
<thead>
<tr>
<th>Object</th>
<th>Subsidence</th>
<th>Tilt</th>
<th>Curvature</th>
<th>Displacement</th>
<th>Extension/Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>House</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Row house</td>
<td>x</td>
<td>x</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machinery</td>
<td>xx</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chimney</td>
<td>xx</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Railway line</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road</td>
<td>xx</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridge</td>
<td>xx</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belt conveyor</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

To clarify the effects of damages specified in Table 6 and to qualitatively assess effects
for each individual object a precise evaluation is required which leads to specific limit
values of ground movements. For the classification of construction objects, evaluation
systems which describe the object-dependent sensitivity towards mining induced
ground movements are already established in the mining areas of Europe. Depending
on various, mostly construction-related object attributes, it is thereby possible to
determine limit values of the maximum object stress. The used classifications are
based mainly on the classification system proposed by Budryk and Knothe (1956).
This classification provides object-dependent limits of the building ground deformation
for the movement elements tilt, curvature and horizontal deformation. These limits
define the basic tolerance of an object regarding ground movements and describe its
ability to withstand the movement impact without risk of losing its function and stability.
Object damages below the threshold values are certainly allowed. Table 7 shows the
object categories and corresponding limit values together with construction type
examples after Budryk and Knothe (1956) and Dzegniuk and Sroka (1978). Objects of
category 0 are very sensitive, however objects of category 5 respond relatively
insensitive to mining interferences.

The assignment of construction examples listed in Table 7 to a particular object
category can be established by a rating scheme with regard to the specific building
construction attributes. The scheme is presented in the following. For delicate objects,
such as monumental and historical buildings, the sensitivity assessment should be
refined by a detailed analysis of the construction and of the building ground. It should
be noted that the final limit definition regarding permissible object stresses is according
to Sroka (2001) and Kratzsch (2002) not only a technical question of object stress
resistance, but rather a compromise between object security (reasonability of
damages), the public acceptance and the economic feasibility of the mining operation.
Table 7: Limit values of ground movements for different object categories after Budryk & Knothe (1956) and Dzegniuk and Sroka (1978)

<table>
<thead>
<tr>
<th>Object category</th>
<th>$T_{\text{limit}}$ [mm/m]</th>
<th>$R_{\text{limit}}$ [km]</th>
<th>$\varepsilon_{\text{limit}}$ [mm/m]</th>
<th>Building examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>50</td>
<td>0.5</td>
<td>Hist. building, power plant</td>
</tr>
<tr>
<td>1</td>
<td>2.5</td>
<td>20</td>
<td>1.5</td>
<td>Industry, memorial</td>
</tr>
<tr>
<td>2</td>
<td>5.5</td>
<td>12</td>
<td>3</td>
<td>Railway track, pipeline</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>Residential house, road, cable line</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>4</td>
<td>9</td>
<td>Storehouse</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 15.0</td>
<td>&lt; 4</td>
<td>&gt; 9.0</td>
<td></td>
</tr>
</tbody>
</table>

To precisely, but nevertheless quickly evaluate and classify building objects, especially in the heavily populated mining areas of Europe with a large number of objects influenced by mining, Dzegniuk at al. (1997), Grün (1998) and others defined and incorporated characteristic object attributes to an assessment system for object classification. According to the assessment system the following construction-related attributes are essential to determine the basic stress resistance of a construction object: length of the object, shape of the building, foundation of the object, features of building ground and of the building construction, building reinforcement and technical condition. The evaluation of each attribute by a point scale (see Table 8) allows the allocation of the analysed object to a category of overall damage sensitivity and thus allows establishing specific limits about tilt, curvature and horizontal deformation.
Table 8: Assessment and classification of building objects regarding to their damage sensitivity after Grün (1998)

<table>
<thead>
<tr>
<th>1. Length of object (building)</th>
<th>Lenght [m]</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>=&lt;10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>5-7</td>
</tr>
<tr>
<td></td>
<td>16-20</td>
<td>8-11</td>
</tr>
<tr>
<td></td>
<td>21-25</td>
<td>12-16</td>
</tr>
<tr>
<td></td>
<td>26-30</td>
<td>17-22</td>
</tr>
<tr>
<td></td>
<td>31-35</td>
<td>23-29</td>
</tr>
<tr>
<td></td>
<td>36-40</td>
<td>30-37</td>
</tr>
<tr>
<td></td>
<td>&gt;40</td>
<td>42</td>
</tr>
</tbody>
</table>

| 2. Shape of structure         | simple (rectangular), connected | 0 |
|                               | simple, nested                   | 3 |
|                               | heavily nested                   | 6 |
|                               | simply, spatially extended       | 6 |
|                               | nested, spatially extended       | 8 |

| 3. Foundation                 | on same level, with and without basement | 0 |
|                               | on different level                 | 3 |
|                               | on different level, partly with basement | 6 |
|                               | as above, with interrupted foundation levels | 8 |

| 4. Ground                     | compressible                        | 0 |
|                               | less compressible                   | 4 |
|                               | incompressible                      | 12 |

| 5. Construction               | rigid                                | 0 |
|                               | less rigid                           | 4 |
|                               | not rigid                            | 8 |

| 6. Reinforcement              | anchorage, concrete bracing          | 0 |
|                               | partly reinforced                    | 4 |
|                               | not reinforced                       | 6 |

| 7. Technical condition        | good                                 | 0 |
|                               | middle                               | 6 |
|                               | poor                                 | 12 |

<table>
<thead>
<tr>
<th>Points total</th>
<th>=&lt;20</th>
<th>21-27</th>
<th>28-36</th>
<th>37-47</th>
<th>&gt;=48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object category</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
7. EIA - Construction of above-ground wellfield facilities

Building the mine facilities starts by prepping the site. Any trees that are in the way need to be cut down and it needs to be ensured that the ground can support heavy vehicles and building foundations. Large boulders need to be moved out of the way and/or broken down into smaller blocks. Also some other backfilling material is likely acquired while digging the building- and pool foundations. This material can be used as landfill outside the mine if it is geochemically and geotechnically suitable, or stockpiled for use during site decommissioning and land reclamation. The stockpiles should be covered with vegetation to avoid dust and excessive land erosion. The pipelines between buildings are commonly installed underground, below 1.8 m, to avoid freezing problems (NRC, 2009). Material from all excavations is commonly assorted into different fractions (like top- and bottoms soils), so that the soil profile can be restored during reclamation stage. In total, the area impacted by the facility can be expected to be somewhere between 50 and 500 ha, based on uranium ISR facilities in the western parts of Wyoming, USA (NRC, 2009).

Further, the site needs to be connected to public utilities and road network. Depending on the location, nearby roads and electrical grids might need to be updated to suit the power draw and heavy traffic induced by the mine. Drinking water needs to be acquired and waste water discarded. This could be done by simply connecting the facilities to an existing water supply network, but at more rural sites an independent system consisting of water purification and waste water treatment plants might be the only viable option.

Overall, environmental impacts from construction of the above-ground well field facilities can be expected to be similar or smaller in comparison to regular mine facilities. Need for piping will be bigger compared to regular mines due to the production wells and pipeline connections between different facilities. Noise generated during the construction stage might be louder and longer lasting than at a regular mine-facilities construction site, mostly due to drilling of the production and observation wells. Some ground vibrations might be produced if explosives are needed to clear the site or while digging building foundations. The severity of the vibrations and noise is generally related to the amount of population living and working nearby. However, after the construction stage (usually months in case of uranium ISR facilities (NRC, 2009), noise and vibrations can be expected to be small compared to regular mines, as the need for explosives, heavy machinery and drilling is minimal.

Other building-stage environmental impacts include emissions from trucks and other equipment, construction waste and dust from uncovered ground surfaces. NRC (2009) estimated particulate (fugitive dust) and gaseous (diesel combustion) pollution from uranium ISR facility construction, see Table 9. However, they also concluded that environmental impacts from both can be considered small in comparison to other industrial operations due to the limited size of the facilities and wellfield construction that is usually phased over many years. However, NRC (2009) noted that the largest source of road-wear and traffic related emissions, noise, dust and incidental livestock and wildlife kills will likely be commuting of facility workers, which will peak during the construction stage. Despite, NRC (2009) further conclude that these impacts can still
be considered small – especially when it’s considered that the duration of the construction stage is limited. As an example, during the construction of Gas Hills uranium ISR facility, heavy traffic was estimated to be about 1 truck per day for a period of two months (NRC, 2004).

Table 9 Estimated particulate (fugitive dust) and gaseous (diesel combustion) pollution from uranium ISR facility construction. The values are based on data from Crownpoint, New Mexico. Estimates from NRC (2009). The values, however, are not completely applicable, as for example dust emissions (Particulate matter) can be considered substantially smaller in Central-Europe, compared to arid New Mexico.

<table>
<thead>
<tr>
<th>Emission type</th>
<th>Annual total (metric tons)</th>
<th>Annual average concentration (μg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate matter</td>
<td>10</td>
<td>0.28</td>
</tr>
<tr>
<td>Sulphur dioxides (SO₂)</td>
<td>6.4</td>
<td>0.18</td>
</tr>
<tr>
<td>Nitrous oxides (NOₓ)</td>
<td>76.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>9.8</td>
<td>0.27</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>63.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Aldehyde</td>
<td>1.4</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Depending on the final site location and its previous state, the facility might impact local wildlife. The three primary impacts can be expected to be (1) the loss, alteration or fragmentation of habitats, (2) displacement of wildlife due to site construction, noise or other disturbances and (3) direct or indirect mortalities from site construction (NRC, 2009). Aquatic environments (if present) can be impacted as well. In this case the highest risks are caused by for example potential fuel spills and increased suspended solids and sedimentation.

Overall, visual impacts of the finished facilities can be considered small when compared to traditional open pit or underground mines. The facility would likely resemble more a factory than a traditional mine. The most substantial facilities and structures needed for site operation are shown in Figure 21.
Figure 21 Required facilities and structures for site operation.
8. EIA - Wellfield operation

8.1. Preparatory phase – flushing steps

The pilot experiments performed in the Rudna mine during the BIOMOre project have demonstrated that before the biolaching starts, a low enough concentration of chloride in the groundwater must be ascertained and occurrences of carbonate rock needs to be removed.

High concentration of chlorides in the groundwater of the mined zone is toxic for the bacteria used in the FIGB. Therefore, a Cl-reduction to below 5 g/l should be done by a simple water wash. Neutral water is injected in the drill holes and water with high concentrations of chlorides are extracted and stored and/or disposed on the surface. In the pilot experiments, the water washing resulted in a pH of about 7.5 and an Eh – value of about -250 mV. These values are similar to the original conditions. The groundwater concentrations of all salts were lowered. In particular, Cl was reduced from 200 g/l to 5 g/l and Na from 130 g/l to 3 g/l. For other constituents the reduction was lower. No rock alteration was observed during the water washing.

With respect to the not processed region there are no thread issues by this flushing step. If there is a preferential connection to other regions in the formation, these volumetrically higher parts will mix up with the diluted water, whereby only small changes can happen. As no chemicals are used in this phase, there is no risk for contamination of the groundwater in the formation.

The bacteria used in the process are acidophilic with optimal living conditions at a pH of about 1.4. Presence of carbonate rocks would buffer the pH at 5 – 6. Furthermore, carbonate rock will dissolve in the injected lixiviant under formation of CO2. To avoid these problems, sulphuric acid is injected into the underground to dissolve the carbonate rock and reduce the pH to ~1.4. As co-process gypsum will precipitate and carbon dioxide will degas.

Figure 22 shows a model simulation the development of carbon dioxide (red), gypsum (green) and calcite (blue) for four layers of the rock matrix representing different distances from the main flow path during injection of sulphuric acid. The distances of the layers from the main pathways (flowing fractures) are:

- Layer 1 - 5 mm
- Layer 2 - 10 mm
- Layer 3 - 15 mm
- Layer 4 - 20 mm

The minerals of rock are altered during the acid injection as calcite dissolves and gypsum is precipitated. The deeper lying rock is less altered. The alteration also influences the pH value. If there are any carbonates remaining the pH stays at 5 – 6. As there are a lot of carbonates in the rock near the leached zone, no acid excursions are expected and thus no environmental risk are expected for the potable aquifer from the injected acid.
Figure 22 Modelling of the development of CO₂, calcite and gypsum during sulphuric acidic leaching in the preparatory phase of the Rudna mine pilot experiments. The layers represent acid penetration depths into the matrix of 5 mm, 10 mm, 15 mm and 20 mm respectively.

In laboratory experiments atacamite (Cu₂Cl(OH)₃) – was observed in rock samples from the Rudna Mine. During the test in the pilot experiments in the mine this could not be reproduced. Nevertheless, atacamite is expected to be readily mobilised under acidic conditions. If we assume a homogeneous occurrence in the rock with a concentration of 3 m-% atacamite, a Copper production during the acidification process of up to 50 % of the total Copper conceivable. At the same time, significant amounts of Cl that may have an important influence on the Cu recovery could become mobile.

Conclusion

Flushing with water

- Dilution of the salts in the groundwater
- No altering of rock minerals
- Low/no changes in pH and Eh
Flush with Sulphuric acid

- Injection of acid causes dissolution of carbonate, precipitation of gypsum, degassing of carbon dioxide
- Low pH stays in the close vicinity of the wellfield, because Carbonate dissolution buffers the propagation effectively
- Possible atacamite aggregation can cause a Cu production already during the acidification process and Cl mobilisation
- Neutralisation of the pH of the wellfield at the end of life of the mining can be done with appropriate additives (e.g. sodium bicarbonate)

8.2. Production phase - ISR wellfield operation

Figure 23 shows a schematic representation of potential migration paths for lixivants and PLS in the described geology, see Chapter 4.

![Figure 23: Schematic of pollutant migration paths from a future copper ISR plant.](image)

Potential pathways or risk modes represented in the figure can potentially lead to leakage and the contamination of the overlying potable aquifers are (the letters A - I refer to the respective pathway in Figure 23 and the numbers in parentheses refer to sections in this report where the respective pathway is treated):

A. Long-term contamination of the formation hosting the ore body (8.2.1)

B. Destruction of the cap rock by uncontrolled fracture generation (6.2)
C. Migration through existing fractures, possibly activated because of mining operations (8.2.2)
D. Leakage around the end of the cap rock (8.2.3)
E. Contamination of potable near-surface aquifers (8.2.5)
F. Migration through damaged wells (8.2.4)
G. Migration via damaged casing cementation (8.2.4)
H. Uplift and subsidence of the overburden (6.2.4)
I. Artificial earthquakes (8.2.6)

8.2.1. A – Long-term contamination of the deposit

During the recovery process, the groundwater in the production zone becomes progressively mixed with the leaching solution (sulphuric acid solution containing ferric iron) and constituents leached from the ore deposit. Thus, elevated concentrations of iron (both Fe^{2+} and Fe^{3+}), sulphur, copper and CO_2 can be expected along with low pH. If the deposit is not neutralised the leaching process is likely to continue for a long time after site-closure, due to high acidity. However, high content of carbonate rocks in the formation will successively neutralise the acid and prevent it from spreading outside leaching zone.

The leaching process also alters the mineralogy of the leaching zone, by removing copper, other metals and soluble minerals. Figure 24 shows the removal of sulphide minerals in the wellfield for layer 1 (5 mm distance to the fracture) and layer 2 (10 mm distance to the fracture). These minerals are the only once, who show significant changes. The sulphides account for only few mass percent of the total rock mass, so that the rock structure is only marginally influenced. It is pointed out that the removal of these minerals is reduced further away from the flowing fractures in the leaching zone.

The removal of the minerals is going on with the alteration of the rock solution. This is demonstrated in Figure 25. The concentrations of Fe, Cu and SO_4 are rising during the bioleaching process. While the Cu and the Fe concentrations are similar in the fracture and in about 3 cm into the rock matrix, the concentration of SO_4 is higher in the fracture than in the rock matrix. This is caused by the addition of sulphuric acid to control the pH value at ~1.4. This simulation does not consider the on-site recovery of Copper. If this is integrated the Copper concentrations in the fracture are reduced, so that a concentration gradient towards the rock matrix is built up and Cu diffuses from the rock towards the fracture. Furthermore, propagation of cations out of the wellfield will lead to formation of hydroxide-minerals in areas with higher pH values.
**Figure 24** Modelling results of the development of mineral amounts during the bioleaching in the Rudna mine pilot experiments. The layers represent penetration depths of 5 and 10 mm respectively.

**Figure 25** Modelling of the development of ion concentrations during the bioleaching for the location Rudna mine pilot experiment.
Conclusion

- There has been developed a complete methodology for risk assessment which is consistent with the scale-up toolbox developed in WP 2. This allows to describe all relevant processes in a hydraulically and geochemically consistent manner.
- The results for a specific scenario described in this document can be summarised as follows:
  - The bioleaching leads to the removal of copper and iron sulphides in the wellfield
  - Leaching outside the wellfield is mitigated by the low propagation speed of the leaching front and the high pH
  - In fact, because of the mineral leaching Cu, Fe and SO$_4$ become mobilised and enriched in the lixiviant solution
  - A propagation outside the wellfield is mitigated by the higher pH, which refers to the precipitation of hydroxide minerals

8.2.2. C - Migration through existing fractures, (possibly activated)

The modelling of transport of contaminants upward through a fracture (fault) requires a higher driving head at the bottom of the fracture than at the top. A model of this must account for differences in salinity over the modelled fracture. Identification of driving forces should include analysis of the occurrence of THMC forces (thermal, hydraulic, mechanical and chemical). This risk mode is evaluated by using the DMT fracture flow model. This would include applying:

- Different scenarios for the hydraulic properties of the formation
- Different geometries of the fracture
- Making assumptions about possible locations of the faults/fractures
- Making assumptions of the extension of the stratigraphic units
- Making assumptions on different hydraulic properties of the fracture/fault

The risk mode that processing fluid migrates through faults or fractures to another geological stratum can be identified by interpretation of measurements and monitoring performed in the site appraisal phase of the operation. Seismic exploration gives information of the location of fault systems. In the next step, the drilling of the wells in the well field, analysis of cuttings, which are pumped to the surface together with the drilling mud, give additional indications of a fault system. Further indications of an active fault systems are pressure losses during the drilling.

Assuming the cap rock is damaged as result of the fracking procedure, leakages can be determined. If the wellfield is flushed by neutral water and the water balance of injected to produced water shows a deficit, this indicates an active connection to other parts of the stratigraphic unit or another stratum of the formation. Usually this can be prevented by a carefully planning of the drilling and fracking actions.
However, the next paragraph shows the case, if a connection to the upper layers is present and shows the effect of several scenarios during the processing of the wellfield.

Calculations with the Reactflow3D model

To estimate the flow-rate caused by leakage over fractures, the geometry of the Weißwasser deposit was simplified with a regular 3D-Model in orientation to the main geological elements. Figure 26 shows a vertical crosscut with the main geological layers and their depths, the fault, and the hydraulic characteristics of the various stratigraphic units. For simplicity the barrier assumed to split the Buntsadstein aquifer in two layers (c.f. Section 4.2) has been neglected in the model. A top view of the model domain is shown in Figure 27.

![Figure 26: Vertical cross section of the simplified model (grey line – fault; white stars – injection drill holes; red stars – observation points; bgs – below ground surface)](image)

<table>
<thead>
<tr>
<th>Legend</th>
<th>Kf-value (m/s)</th>
<th>Porosity</th>
<th>Stratigraphic unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>1.0 \times 10^{-4}</td>
<td>0.10</td>
<td>Quaternary</td>
</tr>
<tr>
<td>Blue</td>
<td>7.5 \times 10^{-10}</td>
<td>0.01</td>
<td>Aquitard</td>
</tr>
<tr>
<td>Green</td>
<td>7.5 \times 10^{-7}</td>
<td>0.05</td>
<td>Sandstone</td>
</tr>
<tr>
<td>White</td>
<td>7.5 \times 10^{-11}</td>
<td>0.02</td>
<td>Cap rock</td>
</tr>
<tr>
<td>Yellow</td>
<td>1.0 \times 10^{-6}</td>
<td>0.06</td>
<td>Leaching zone</td>
</tr>
</tbody>
</table>

*Figure 26 Vertical cross section of the simplified model (gray line – fault; white stars – injection drill holes; red stars – observation points; bgs – below ground surface)*
The model uses the separate “fault modelling procedure” of Reactflow3D as a double-permeability-system. The fault is in the basic scenario described as an open fracture i of 2 mm width that connects the ore deposit layer with the potable Quaternary aquifer. Further parameter variations are shown at the end of this section. In the basic scenarios and scenario (V1-V5) the fracture is assumed to obey the so called cubic-law. In variant V6 the fracture is assumed to follow the gradient dependent turbulent law with hydraulic smooth surfaces.

To evaluate the development of head gradients and the migration of pollutants to the overlying aquifer, a total leachate flux of 32 m$^3$/hr in the leaching zone (white stars in Figure 26 and blue star in Figure 27) over a time period of 2 years. The injected fluid contains a Zn concentration of 100 mg/l representing a generic tracer element used to evaluate the development of the concentration in the overlying geological layers. It is assumed that the input and extraction boreholes are not hydraulically connected. This assumption is conservative with respect to the build-up of pressure head in the leaching zone as the injected water must migrate through the geologic strata, including the fracture/fault instead of being extracted via the extraction wells.

The calculations were carried out with and without density effects. In the case with density effects the salt concentrations in the various parts of the formation were assumed to be:

- Aquitard/sandstone/cap rock: $C_{Cl} = 1000$ mg/l, $C_{Na} = 100$ mg/l
- The leaching zone: $C_{Cl} = 134000$ mg/l, $C_{Na} = 84718$ mg/l
The resulting development of pressure head in observation points are given in Figure 28 and Figure 29. The observation points are:

- At the fluid injection point ($h_{\text{pump}}$)
- At the foot of the fault ($h_{\text{fault_foot}}$)
- In the fracture, halfway to the top ($h_{\text{fault_middle}}$)
- At the bottom of the top aquifer ($h_{\text{fault_GWL}}$)

In addition, the injection flow rate has been plotted, see orange line with scale on right hand y-axis in Figure 28 and Figure 29. The results are expressed as “equivalent freshwater head”, below called head for simplicity.

When leachate is injected, the head increases. The increase of head stops after 2 years when the fluid injection stops. In the case “with density effects” the initial head in the leaching zone is higher than in the overlying layers and higher than the initial head in the “non-density calculations”.

![Figure 28 Development of pressure head (with density-effects)](image_url)
Figure 29 Development of pressure head (without density-effects)

The development of the zinc and chloride concentrations with and without the density effect is shown in Figure 30 to Figure 33.

The zinc concentration at the injection point increases as leachate is injected. After about 1.5 years the zinc concentration at the foot of the fault starts to slightly increase. The zinc then rises only a few tens of metres in the fault. In principle, the development of chloride is similar to that of zinc with two differences:

- The chloride concentration of the leachate is low and that’s why chloride is washed out in the nearfield of the injection drill-hole.
- Because chloride is at the beginning distributed in the entire leaching zone, the rising movement in the fault starts earlier than for zinc.

The calculation considering the density-effect shows that the movement in the upper regions of the leaching zone is faster than at the bottom. Due to the lower density of the injected fluid, it tends to move upward until it is stopped by the cap rock.
Figure 30 Development of Zinc (with density-effects)

Figure 31 Development of Zinc (without density-effects)
Figure 32 Development of Chloride (with density-effects)

Figure 33 Development of Chloride (without density-effects)
Figure 34 to Figure 37 show the distribution of zinc and chloride three years after the start of leachate injection (one year after the injection ceased) in the vertical cross section without and with density effects respectively. The legends show the concentration in mg/l on a logarithmic scale. The zinc front reaches nearly the -500 m-level, but the concentration is only $1 \cdot 10^{-6}$ mg/l, which is a factor of $1 \cdot 10^{8}$ lower than the 100 mg/l in the injected leachate.

During the 2 years of leachate the front of chlorides and zinc never reached the sandstone nor the Quaternary layer and one year after the cessation of the injection, the fronts had retracted slightly.

**Figure 34 Concentrations of chloride (mg/l) after 3 years (without density), log-scale**
Figure 35 Concentrations of zinc (mg/l) after 3 years (without density), log-scale

Figure 36 Concentrations of chloride (mg/l) after 3 years (with density), log-scale
The following diagrams document different variations of parameters: fracture width, permeability of the deposit, and boundary conditions. On the next pages each variant is presented by a head diagram followed by a zinc diagram. In the density cases the pressure head is equal to the “equivalent fresh water head”. All variants are based on the “basic scenario” with changes of single parameters. The basic scenario parameter values are:

- \( k_f \) – value \( 1 \cdot 10^{-6} \) m/s
- Fracture aperture 2 mm
- Turbulence law: cubic law

The values of the varied parameters in each of the variants are shown in Table 10.

Table 10 Summary of the adapted parametrisation for the variant simulations describing the propagation of Zinc and Chloride

<table>
<thead>
<tr>
<th>Variant</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Fracture aperture</td>
<td>1 mm</td>
</tr>
<tr>
<td>V2</td>
<td>Fracture aperture</td>
<td>3 mm</td>
</tr>
<tr>
<td>V3</td>
<td>Storage coefficient of the boundary condition (equivalent to the extension of the leaching zone)</td>
<td>Reduction of 50%</td>
</tr>
<tr>
<td>V4</td>
<td>( k_f ) – value leaching zone</td>
<td>( 1 \cdot 10^{-7} ) m/s</td>
</tr>
<tr>
<td>V5</td>
<td>( k_f ) – value leaching zone</td>
<td>( 1 \cdot 10^{-5} ) m/s</td>
</tr>
<tr>
<td>V6</td>
<td>Turbulence law</td>
<td>Hydraulic smooth</td>
</tr>
</tbody>
</table>
V1: fracture width 1mm:
V2: fracture width 3mm:
V3: Porosity_Boundary Element 50% of basic-scenario

![Graph showing h_Q with density and c_Zn with density](image-url)
V4: Permeability of the leaching zone $1 \times 10^{-7}$ m/s (Note: Y-axis scale differs)
V5: Permeability of the leaching zone $1 \cdot 10^{-5}$ m/s
V6: Real turbulent law: “hydraulic smooth”

![Diagram 1](h_Q - with density turbulent - "hydraulisch glatt")

![Diagram 2](c_Zn - with density)
Scenario V5 gives the greatest propagation of the zinc front because this is the scenario with the highest permeability in the leaching zone. However, the influence on the Buntsandstein and the other overlaying strata is negligible.

The scenario calculations with parameter combinations of possible uncertainties showed no influences on the potable aquifer. Therefore, it was conducted another, not realistic, simulation to present the typical plume distribution. The changes of model parametrisation cover:

- Closed boundary at the top of the leaching zone (tight cap rock)
- Increase of injection time to 10 years

Figure 38 shows the distribution of Zinc at the end of the ten years injection period. A majority of the zinc stays in the leaching zone. The propagation of the plume upward through the fault occurs in low amounts only. The concentration at the point where the fault enters the first sandstone aquifer will only reach 1/1000 of the original concentration. From this point the plume will spread laterally at the bottom of this aquifer. There is no risk for contamination of the potable Quaternary aquifer.

Conclusion

- A complete methodology for risk assessment, consistent with the scale-up toolbox developed in WP 2, describing all relevant processes in a hydraulically and geochemically consistent manner, has been developed.
- No risk for contamination of the potable Quaternary aquifer from the injected leachate with all dissolved ingredients to the could be observed despite the conservative that no extraction of liquid through the extraction
wells, i.e. all injected fluid must leave through the geological strata including the fault. The reasons for this can be summarised as follows:

- Injection at great depth and
- density effects result in
- low flow rate.

8.2.3. D - Variable cap rock thickness / end of cap rock gives upward migration of fluid from the leaching zone

Figure 39 presents a stratigraphic profile of the Fore-Sudetic Monocline. The pilot test of BIOMOre project takes place in the Rudna mine in the northern part of the monocline. The ore horizon is overlain by a caprock consisting of low permeability Zechstein limestones in combination with impermeable strata consisting of anhydrites, mudstones and rock salt. This creates hydrogeologically favourable conditions for application of the ISR technology. The horizontal extent of the cap rock renders end of barrier leakage in this case a low probability.

The Zechstein limestone stratum, P2P in Figure 39, sits directly on the deposit. The Zechstein limestones constitute a water-bearing horizon that is the main source of the water used in the current mining operations at Rudna and other mines in the area. The stratum is separated from the other water-bearing horizons by impermeable rocks (anhydrites, mudstones and rock salt). In the ISR process, the lixiviant that is introduced in the deposit will be hindered from spreading upwards by this caprock. The thickness of the caprock varies from a few metres in the northern part to as much as 100 metres in southern part of the Fore-Sudetic Monocline. The northern part of the caprock is characterised by low fracturing, low porosity and low permeability \((k=1\cdot10^{-9} - 1\cdot10^{-7} \text{ m/s})\). The southern part is more fractured with higher porosity rocks and higher permeability in the upper part where the caprock comes closer to Tertiary rocks (Tr in Figure 39).

8.2.4. F, G - Migration via pre-existing wells and wells in the operating well field

The casing tubes in both the injection and the extraction boreholes will be cemented against the surrounding rock. During the project a review of the materials that could be utilised to cementation of drillings (injection and production wells) was made. The concern was the risk of contact between the cementation material and the strongly acidic solutions used in the ISR process.

Casing tubes are usually cemented using standard cement. The cement components can react with the sulphuric acid in the lixiviant and the PLS in a way that changes the physical and chemical properties of cement. As long as the casing tubes are intact and tight, contact between the cementation material and acidic solutions would be possible in the deposit. Therefore, traditional cementation materials can be used for the whole length of the boreholes except for the leaching zone where the casing is penetrated by during the stimulation phase, Section 3.4.5.

In the leaching zone, should be made using that are resistant to long-term contact with sulphuric acid. There are currently practically no materials with acid resistance certificate available on the market. The materials that could be applicable are described below.

Summarising the review of materials, the injection and collection wells can be secured with utilisation of commonly used technology of cementation with cement filling except in the leaching zone in the deposit. In the leaching zone, other acid resistant materials should be used to secure the wells.

Only one of the materials reviewed, the silicate resins Krzemopur HS, was tested for long-term sulphuric acid resistance. After confirmation of its resistance properties it was applied in BIOMOre project pilot experiments in the Rudna mine. The acid resistant properties of other sealing materials have yet to be tested.

**Silicate resins**

Silicates are characterised by their high stability and rapid strength development. They are suitable for mechanical cutting and planning after a very short curing time.
The material tested for sulphuric acid resistance was Krzemopur HS from Minova Ekochem. The tests were conducted by AGH University of Science and Technology in Kraków (Wiśniowski et al., 2016). The product is a two-component silicate-isocyanate system, utilised to reinforce and seal fragile and weak strata, and also to seal against water and gas leakages. The product was immersed in 7% sulphuric acid solution for 72 days. The tests showed that this material is long-term resistant to the sulphuric acid.

It was already used to secure the injection and collection holes in the BIOMOre pilot scale experiment in the Rudna mine. There are also other manufacturers of silicate resins, e.g. Inter Chemol (Górosil AS, Chemopur Flex), WEBCA (SILcompact) and others.

**Expandable silicate resins**

Expanding silicate injection foam resins are utilised for temporary sealing of foundation pits and tunnels, subsoil and rock mass stabilisation. Foams are suitable for mechanical machining. They react with and without water contact. The foams are characterised by high foaming factor and fine cellular structure. They are suitable for cutting and planning, and they have low viscosity and short reaction times.

**Polyurethane resins**

Are used for the closing, sealing and limited-flexibility bonding of structural elements. The PU resin are characterised by its high chemical resistance. It is especially designed for use in case of high chemical stress, for instance for canal repairs. The material is known for its short-term resistance for sulphuric acid, but it can differ depending on the manufacturer.

**Phenol formaldehyde resins (PF)**

Phenol resins (foams) are utilised worldwide in fire and methane prophylaxis as the sealing and filling material. The phenol resins are applicable to sealing of the workings, building and sealing the ventilation and isolation dams, filling of voids and much more. The acid resistance of this product is not yet confirmed and must be tested.

8.2.5. E -Total risk of impacts on protected/sheltered groundwater resources

This risk mode combines all modes of transport from the ore deposit to the overlying potable aquifer. The evaluation of the exposure was done by a probabilistic transfer function approach in which a contaminant mass input at location $i$ is converted to a concentration in a drinking water well $j$:

$$ \dot{m}_i(t) \rightarrow c_j(t) $$

(6)

As can be clearly seen (see section 8.2.2), for the current setting, there will not be any migration of harmful substances from the reservoir to the potable aquifer. Despite of this, there was developed a consistent methodology which is capable to simulate the migration in the potable aquifer. For these simulations there have been assumed mass fluxes from the Buntsandstein formation in the range of 1mg/s to 1 g/s Zn to
demonstrate the methodology, only. Zn was chosen as representative of the plume propagation in analogy with the evaluation in section 8.2.2. The maximum concentration is 100 mg/l.

The evaluation is based on several uncertainties. Next to the mass flow into the aquifer, it was identified the following parameter, supplemented with the analysed bandwidth.

- Aquifer properties:
  - kf-value \(1 \cdot 10^{-6} \text{ m/s} - 1 \cdot 10^{-4} \text{ m/s}\)
  - hydraulic gradient 1\% - 1‰
  - porosity 15\% - 40\%
- downstream distance to the drinking water well 10 m - 1000 m

The propagation through the aquifer is calculated with Darcy’s law. A fresh water injection and a contaminant mass flux from the solution in the deposit are considered. It was assumed that the injection of lixiviant is stopped after 3 years. The total simulation time covers 50 years. The simulation is repeated 1000 times, each time with new combination of parameter values sampled from the intervals given above.

Figure 40 shows statistics of the concentration of zinc in the drinking water well as a function time. The upper bound of the light red area represents the highest simulated concentrations in the well while the top upper bound of the deep red area represents the 90-percentile of the simulated values. The 90-percentile exceeds 10 mg/l only between the 1000th and 2500th day. The median (50-percentile) is close to 0 mg/l over the whole period simulated while the mean value of 6 mg/l to 7 mg/l (red line) is biased by the few simulations yielding high concentrations.

In a second evaluation, the maximum concentrations of zinc in the drinking water well as a function of time were simulated. In this second evaluation, the concentration in each realisation increases to its maximum and stays at this value to the end of the realisation. This measurement allows an assessment of the probability of an impairment of the water quality in the ore deposit. The result resulting statistics is presented in Figure 41. The 90-percentile of the maximum Zn concentrations is higher than the 90-percentile of the time dependent concentrations in the well. After 50 years (at the end of the simulated time) the 90-percentile is 60 mg/l, the 75-percentile is at 15 mg/l and the 50-percentile at about 1mg/l. That means for 50% of the realisations the peak concentration of the plume is diluted with a factor of 100 or more.
**Figure 40** Time dependent statistics of the Zn concentration in the drinking water well.

**Figure 41** Time dependent statistics of the maximum Zn concentration reached in the drinking water well.
The mass flow of Zn into the aquifer and the distance from the fault to the well were identified to be the most important parameters leading to high concentrations in the well. Figure 42 shows the Zn concentration after 5 (highest probability of high Zinc concentrations) and 50 (simulation end) years as a function of these two parameters. It becomes clear in both diagrams that the combination of a high mass flow into the aquifer with a short distance to the drinking water well (red dots) yields high Zn concentrations in the well. Reduction of the mass input (pink dots) as well as an increase of the well distance from the input zone (green dots) result in a reduction of the Zinc concentration. The combination of distances above 100 m and an input below 100 mg/s (blue dots) gives no risk for the water quality for drinking water wells. A comparison of the results after 5 years diagram after 50 years shows only slight changes. There are less red and pink dots representing high concentrations after 50 years while the number of green dots increased. Figure 43 shows that the distance fault to well refers to significant retardation of the maximum concentrations. In some realisations the maximum concentration was not reached even after 50 years.

**Figure 42** Distribution of the Zn concentration in dependency of the distance to the well and the mass input at the fault after 5 years (left) and 50 years (right)
Conclusion

- A complete methodology for risk assessment has been developed, which is consistent with the scale-up modelling toolbox developed in WP 2. This allows to describe all relevant processes in a hydraulically and geochemically consistent manner.

- The results for a specific scenario described in this document can be summarised as follows:
  - Because of the results of section 8.2.2 that no deposit solution will reach the potable aquifer, an evaluation of assumed mass fluxes was conducted. This means the evaluation is theoretical. There is no potential risk for the aquifer.
  - The main factors for the impairment of the aquifer are the mass flux of the contamination and the distance to a drinking water well, whereby the distance has rather a retardation effect.

8.2.6. 1 - Induced Seismicity

Induced seismicity, that is seismicity generated or triggered by human activity, acts on pre-existing rupture and fault planes in the subsurface at all scales. In principle, each single rupture zone can be activated, if the shear stress acting on the rupture plane overcomes the motional resistance of adjacent rock formations. In most cases, the shear resistance (or shear strength) depends on the principle of friction. This means that the shear resistance is proportional to the difference of the normal stress (σ) acting
on the plane to the pressure (p) of the fluid that penetrates the fault area and the surrounding rock (Figure 44, a)). The fault area is stable (meaning no movement on the rupture plane), until the shear stress (τ) is smaller than the friction μ(σ-p). Herein, the term (σ-p) is called the effective stress. μ is the friction coefficient that normally ranges between 0.6 and 0.8. This condition for the triggering of displacements on a rupture plane is called the Coulomb criterion (Figure 44, b). Therefore, the parameters controlling the start of movement on the rupture plane with the frictional coefficient μ are normal stress, shear stress and fluid pore pressure. Normal and shear stress are depending on the orientation of the rupture plane and the general stress state of the overburden.

The stress state in the underground can be described by three principal stresses. Normally, one of the principal stresses is orientated vertically, which is then termed σv. The minimum and maximum horizontal stresses are termed σh and σH. The direction of σH as well as the values of σv, σh and σH define the orientation of the plane in the undisturbed overburden that is most likely to break (Figure 45).

Figure 44 (a) Shearing of a merged block that is exposed to the normal force FN and the shear force Fs. The contact plane is filled with a fluid under the pressure p. Movement along the contact plane is triggered, if the shear stress τ equals the frictional resistance μ(σ-p); (b) Visualisation of the Coulomb criterion: No movement occurs, if the “point” (σ-p, τ) lies below the critical line, defined by the gradient μ. (NAS, 2012).
Seismicity connected to hydraulic fracturing operations normally lies in the magnitude range below $M = 0$ (Warpinski, 2009; Maxwell, 2013). Seismic events of this small size are usually not felt at the surface. Stronger events that can be felt at the surface occur only very rarely (Luza and Lawson, 1990; Holland, 2011). During stimulations with very large amounts of water in Oklahoma two events with magnitudes $M = 2.3$ and $M = 1.5$ were triggered, followed by a larger number of small events. In the last years, the rate of seismic events of magnitudes $M > 3$ that are probably connected to waste water disposal has increased to a few hundred every year$^4$. However, during tens of thousands of other stimulations (NAS, 2012) a maximum magnitude of $M = 0.8$ could be observed. The reason for the rare occurrence of larger magnitudes lies in the source mechanism of these events. Seismic events start close to the injection location (the location of stimulation). The strength of a seismic event depends on the size of the (activated) rupture area and therefore also on the injected fluid volume.

The crack opening created by the stimulation can create ruptures at the crack tip as well as ruptures on pre-stressed small planes (length scale: millimetres to some metres) by the moving pressure front (Figure 46). A movement on these small planes creates the observed micro seismicity ($M < 0$). Thereby, the process of the crack opening itself is not seismically active.

---

Figure 46 Crack propagation during stimulation. The resulting pressure front induces shear movement at the crack tip and on pre-stressed faults (red). Modified after Bohnhoff (2015).

In case of an injection in proximity of large scale faults under unknown pre-stress conditions, migration of the fluid can trigger shearing on these rupture planes (length scale: tens of metres to some kilometres; Figure 47). The reason is the following

\[ \sigma_e = \sigma_n - p_f \]  

with

- \( \sigma_e \) = effective normal stress,
- \( \sigma_n \) = normal stress and
- \( p_f \) = pore pressure of the fluid.

The pore pressure of a fluid on the rupture plane acts against the normal stress and therefore reduces the effective stress. A necessary requirement is that the rock formation in the rupture area has a sufficiently high shear modulus. Therefore, the rock must be able to store stresses of a certain amount that are released during the rupture process. Hence, the size of the area where the pressure of the injected fluid overcomes the normal stress on the rupture plane and thus enables shearing on these planes is essential (see Figure 44).
Figure 47 Fluid-induced seismicity caused by increasing pore pressure (green arrows) acting opposite to the normal stress (brown arrows) on a critically stressed rupture plane.

After fluid injection, the pressure in the underground drops with a time delay. The drop of the pressure curve flattens out with increasing distance to the injection point, at the same time the fluid front broadens. In summary, this can lead to the triggering of rupture processes that overcome the size of ruptures during injection even after the end of injection. For this reason, the strongest seismic events often occur after finishing of the stimulation phase.
9. EIA - Operation of surface facilities

The surface facilities of the assumed commercial scale ISR facility include operations for lixiviant regeneration, metal recovery, waste treatment and various auxiliary facilities, see Figure 48. The processes are briefly discussed in Sections 3.4.8 – 3.4.10. The installations can be assumed to cause leakages and discharges of various agents used in the process, e.g. lixiviant solution including acidophilic microorganisms, other substances utilised during metals recovery such as organic solvents used in solvent extraction (SX). While controlled discharges to recipients are expected to occur and thus will be subject regulation and monitoring, leakages are may be referred to as accident situations. Risks for accidental spills must be accounted for in the design of a future facility such that proper counter measures are taken to prevent spills and to mitigate their impact on human health and the environment.

**Figure 48** Overall flow sheet assumed for the commercial scale implementation of the BIOMOre technology. The extent of the operations of the surface facilities has been indicated with a blue frame.

In the following impacts of discharges and leakages are discussed for three steps of the operations:

- Handling of lixiviant and pregnant leach solutions
- metal recovery, and
- waste management.

9.1. Handling of lixiviant and pregnant leach solutions

The handling of lixiviant and PLS includes storage of the solutions in ponds for settling of particulates, regeneration of lixiviant in bioreactor including addition of make-up chemicals, transfer of lixiviant to the injection wells, and transfer of PLS from the extraction wells. About 15% of the PLS stream is withdrawn for metal recovery.
Before injection the lixiviant is oxidised in the bioreactor to convert the iron content to trivalent, and make-up chemicals are added to compensate for losses in the product recovery. The content of free acid the injected lixiviant will be in the order of 3 g/l (Hatch Associates Ltd., 2016). It will also contain ferric iron and minor amounts of acidophilic microorganism carried over from the bioreactor. The microorganisms used are non-pathogenic.

The composition of a typical pregnant leach solution (PLS) has been estimated from mass balance calculations (Hatch Associates Ltd., 2016). The results show that PLS will consists of Cu in the order of 4 g/l with an uncertainty range of 1,5 g/l to 5 g/l depending on small variations in the assumptions. The solution will also contain other elements such as Zn (~0,05 g/l), Co with a concentration in the order some mg/l, and a mixture of ferrous and ferric iron originating from the oxidation agent added to the lixiviant. The solution will be acidic and contain minor amounts the acidophilic and non-pathogenic iron-reducing bacteria carried over from the bioreactor population. In addition, it is expected that the PLS will contain a variety of elements from the reaction between the lixiviant and the gangue rock types in the ore horizon.

The transport of the pregnant leach solution (PLS) from the collection wells to the PLS pools and of lixiviant from the lixiviant pools to the injection wells will be carried out with pumps and in pipelines designed for acidic strongly solutions. As the risk for leakages is primarily associated with off-standard events, it is important that special precautions and procedures are implemented to avoid potentially dangerous situations and that a preparedness to enter mitigation procedures to reduce their impact is maintained.

9.2. Metal recovery

Potential flow sheets for production of copper from Kupferschiefer ore have been presented in Section 3.4.9. Three flow sheets would have been judged to have a greater potential than others to be economically viable:

- Sequential sulphide precipitation.
- Recovery by ion exchange (IX) preferentially followed by electrowinning (EW) or, potentially, by sulphide precipitation.
- Recovery by solvent extraction (SX) followed by electrowinning.

All three technologies require (Figure 48) a pre-concentration step that is likely to involve membrane technologies, removal of a bleed stream to control the content of disturbing substances in main process stream, a unit for treatment and recirculation of the barren process solution, and a facility for treatment of effluents and waste generated.

The three technologies make use of different agents out which some are hazardous substances, e.g. see Table 11. These substances will under normal operating conditions be controlled either in closed circuits or in monitored process streams.
Effluents and other discharges will be regulated in the permitting and the subsequent authority monitoring of the facility. Leakage of larger quantities are expected to be associated with accident situations only. Appropriate procedures must be in place for the prevention of such accidents and the mitigation of impacts on human health and the environment from accidents that occur despite the preventive procedures.

The bacteria and archaea used in the bioreactor occur naturally in the sub-surface and in sulphide minerals deposits. The activity of acidophilic bacteria depends on specific environment conditions where the oxidation of iron (II) and sulphur (to sulphates) compounds proceed only in acidic environments. At pH > 3.0 their metabolic activity is reduced and eventually stops. It means that during the spillage natural conditions will cause inhibition of their activity. In addition, the microorganisms are non-pathogenic. Summarising, the hazards associated with the release of microorganisms are negligible.

<table>
<thead>
<tr>
<th>Process (example)</th>
<th>Substance (examples)</th>
<th>Environmental hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>Sulphuric Acid</td>
<td>Etching hazard to personnel. Harmful to aquatic life in very low concentrations. Hazardous short-term degradation products are not likely while long-term degradation products may arise, primarily sulphur oxides (SO₂, SO₃). These degradation products are gases.</td>
</tr>
<tr>
<td>SX</td>
<td>Organic solvent (e.g. solution of kerosene and D2EHPA)</td>
<td>The relative environmental impacts of Kerosene: acute toxicity (medium), mechanical injury (Medium-Low), persistence (Low). Release of this product should be prevented from contaminating soil and water and from entering drainage and sewer systems.</td>
</tr>
<tr>
<td>Sulphide precipitation</td>
<td>Hydrogen sulphide gas</td>
<td>Acute toxicity to personnel (alarm devices should be considered). Very toxic to aquatic organisms. Endangering to drinking water. Avoid release to the environment. Product is not allowed to be discharged into ground water or the aquatic environment.</td>
</tr>
<tr>
<td>IX</td>
<td>Resins (e.g. DOW XUS-43605)</td>
<td>In the terrestrial environment, ion exchange resins are expected to stay in the soil. In the aquatic environment, material will sink and remain in the sediment. Surface degradation is expected with exposure to sunlight. However, no appreciable biodegradation is expected. Contact with ion exchange resins is not expected to be acutely toxic to aquatic species and waterfowl. However, ingestion of beads may cause adverse effects in some species</td>
</tr>
</tbody>
</table>

### 9.3. Waste treatment

The operation of the surface facilities will give rise to both solid and liquid waste streams. In Section 3.4.10 some possible principles for treatment and disposal of process waste are described. Such waste management procedures will in a future production facility be regulated according to the legislation in place at the time of licensing. The BIOMOre project has not explicitly addressed the process waste management issue. Hence, there is no possibility to quantitatively assess the environmental impacts from the waste management.
10. **EIA - Wellfield closure and reclamation**

Upon wellfield closure the production and injection wells will be filled with concrete to limit migration of possible residual contaminants through them and to block unnatural flow paths of groundwater. On the ground surface the wellfield structures will be dismantled. Above the ground well casings should be cut to a suitable length and capped. Any contaminated soil should be remediated using BAPs. Remediation goals should be based on pre-production baseline values, but also consider plans for post-operational land use (NRC, 2009). NRC (2009) shows estimates for by-product and municipal waste amounts from uranium ISR facility and wellfield closure, Table 12.

Table 12 Estimated amounts of by-product and municipal waste from uranium ISR facility and wellfield closure. The estimates are based on Smith Ranch uranium ISR facility, located in Wyoming, USA. Estimates from NRC (2009).

<table>
<thead>
<tr>
<th>Decommissioning step</th>
<th>By-product wastes (m³)</th>
<th>Municipal wastes (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing equipment removal</td>
<td>261</td>
<td>0</td>
</tr>
<tr>
<td>Building demolition</td>
<td>417</td>
<td>406</td>
</tr>
<tr>
<td>Wellfield equipment removal</td>
<td>1041</td>
<td>309</td>
</tr>
<tr>
<td>Trunk line removal</td>
<td>1730</td>
<td>0</td>
</tr>
<tr>
<td>Contaminated soil removal</td>
<td>1092</td>
<td>0</td>
</tr>
<tr>
<td>Evaporation pond reclamation</td>
<td>52</td>
<td>0</td>
</tr>
</tbody>
</table>

After dismantling of wellfield structures, the ground surface should be recontoured, the original drainage should be re-established and vegetation such as grass or willows should be planted on the site (NRC, 2009). The short, capped metal pipes and many observation wells used to monitor the groundwater conditions should be the only indications of the wellfield after successful remediation. After the site has reached a steady state, it can be released for unrestricted use and can be used for example as building grounds or farmland.

10.1. **Clean-up**

Current experience from clean-up after ISR operations comes primarily from uranium extraction. The chemical clean-up process has been noted to be highly site specific even between different uranium ISR facilities (EIA, 1995). This means that the actual clean-up process might considerably differ from the one outlined in this chapter. However, the remediation goals should always be based on pre-production baseline values. Natural variation in groundwater quality between different wells should also be considered while setting these goals. In the present case deep-lying ore deposits are being targeted. In such cases the background groundwater quality is usually poor with *inter alia* high salt concentrations.

After the metal production at the facility has ended, a clean-up process of the affected rock volume should begin immediately to avoid uncontrolled contaminant migration. The clean-up process is usually conducted in several steps that will typically involve...
denaturing of the groundwater by injecting a suitable bacteriocidic solution, sealing off open fractures by, for example, chemical precipitation, cleaning the mining zone by flushing and sealing off the hole. The clean-up process is usually the most expensive part of the site closure and reclamation (EIA, 1995).

If a wellfield is closed only partially and a new wellfield is opened next to it, the clean-up process should begin by circulating water between the two fields. This introduces the mining fluid into the new zone and reduces lixiviant and metal concentrations in the decommissioned field. As a result, the old and new wellfields should show similar chemical compositions to one another (NRC, 2009).

Schippers and Ballerstedt (2017) suggest for the denaturing step injection of a mixture of formic acid, 1-hexanol, sodium chloride and sodium dodecyl sulphate. Experiments indicated that replacing the formic acid with acetic acid would give a less efficient denaturing solution. Further, calcium chloride can be added to the solution to promote sealing of fractures by precipitation of gypsum (Schippers and Ballerstedt, 2017), but this might also be unwanted until the very end of the clean-up process. Problem with the added chemicals is that they might induce new contaminants into the system, which then need to be considered in the clean-up process (EIA, 1995).

In the next step, the closed mining zone is flushed with baseline-quality groundwater. This is achieved by pumping water from all production and injection wells without re-injection. The inflow of native groundwater cleans the production zone from dissolved metals and remaining lixiviant (NRC, 2009). The contaminated groundwater should then be treated similarly to the waters from the production stage. Metal- and lixiviant concentrations should decrease over time as the flushing proceeds (Davis and Curtis, 2007). The duration and required pumping rates vary depending on the site conditions, but the flushing should continue at least long enough to replace the whole pore volume of the production zone several times over (EIA, 1995; NRC, 2009). The biggest problem with the flushing step is that it produces waste water often many times more than the actual production cycle does. This means that suddenly, after the production has ended, large volumes of water need to be treated in the clean-up process (EIA, 1995).

If a sufficient water quality cannot be achieved only by washing, a reverse osmosis step is usually added. The reverse osmosis process can be used to alter pH, and to effectively reduce total dissolved solids and trace element levels to near baseline values (Davis and Curtis, 2007). Because of the treatment, water is separated into two fractions. The larger portion (usually about 70%) of the water is fairly clean and is commonly re-injected into the same stratum. The rest (around 30%) is enriched with metals and should be discarded in the same process as production phase waste water (NRC, 2009). With added cost, an additional brine concentrator can be used to treat the rejected fluid. This reduces the volume of rejects to below 1% with a brine-like composition (NRC, 2009). Thus, as a large portion of the water can be re-injected into the mined zone after the reverse osmosis process, it might be beneficial to apply the method already during the flushing process to make the amount of waste water smaller (EIA, 1995). Water injection rates can remain fairly high during the process (up to hundreds of litres per minute), but the pore volume in the treated stratum needs to be replaced usually at least ten times for desired results (NRC, 2009).
The biggest problems with reverse osmosis are that it is expensive and that the semi-permeable membranes of the system are prone for fouling, meaning that the water often also need to be pre-treated before the actual treatment process (NRC, 2009). In the BIOMOre project, Hatch Associates Ltd. (2017) evaluated different membrane technologies for pre-concentration of PLS before entering the metal recovery circuit. The results from this study may be applicable to the treatment of extracted clean-up water.

The pre-treatment includes limiting the precipitation of minerals (e.g. by adding calcium carbonate). Also, antiscalants such as sodium hexametaphosphate or polycarboxylic acids are commonly added. The pH of the water needs to be lowered for the process, which can be achieved with, for example, sulphuric acid. After the reverse osmosis, a base such as sodium hydroxide can be added to readjust the pH of the groundwater close to baseline values (NRC, 2009).

10.2. Post closure monitoring

A post closure monitoring program should be implemented to assess the effectiveness of the remediation process and to determine when long term steady-state conditions have been reached (EPA, 2014). Groundwater conditions should be monitored both in the active treatment zone and outside the boundaries of the impacted area. Monitoring should also include all strata located above or below the treatment zone to capture possible vertical fluid migration. The monitoring should include regular sampling and estimations of groundwater flow paths and velocities. Samples should be collected at least four times a year and it should be considered if, for example, the post-mining sampling and sample analysis methods match those of the pre-mining period, and if not, if the results are readily comparable (EPA, 2014). Proper observation well placement and knowledge of the pre-mining hydrogeological and hydrogeochemical conditions are acting as key factors while trying to determine if the remediation goals have been met (EPA, 2014).

Computer models, such as groundwater flow models and reactive transport models, can be used to assist the monitoring process. Models can be used to for example aid in observation well placement and to estimate the length of the monitoring period. Statistical methods such as the Mann-Kendall test for trends, can be used to demonstrate the stability of the conditions at the end of the monitoring process and to compare the post- and pre-mining conditions to one another (EPA, 2014).

The monitoring period should last for at least as long as needed to capture seasonal variations. EPA (2014) notes that with uranium ISR projects the restoration processes have often been complex and results have varied depending on site specific hydrological and geochemical characteristics. This has led to a situation where, in some cases, the post closure monitoring period has had to be extended from the estimated timeframe by years.

Additionally, the site should be monitored for signs of land erosion and ground subsidence, latter of which can occur due to empty volume in the subsurface. Ground subsidence can be monitored for example with regular satellite images taken by
synthetic aperture radar. The surface deformation or other changes that may have occurred can be observed in differences between multiple images.
11. Discussion

This report presents a review of environmental impacts from a possible future commercial size facility where the BIOMOre technology is assumed to be used for in-situ recovery, ISR, of metals by bioleaching. The review of impacts has, to the greatest extent possible, followed the formalism of an Environmental Impact Assessment, EIA, as it is described in European legislation. According to this legislation, the EIA should identify, describe and assess the direct and indirect significant effects of a possible future commercial size facility for metal ISR on:

- population and human health,
- biodiversity,
- species and habitats,
- land, soil, water, air and climate,
- material assets,
- cultural heritage and the landscape, and
- the interaction between the impacts.

The review has spanned over the life cycle of an ISR project starting when an ore deposit has been identified. The first step of the life cycle is then an appraisal and delineation of the deposit followed by the construction of the ISR facility under ground and above ground. The operational phase then includes circulation of lixiviant through the deposit, withdrawal of pregnant leach solution, PLS and hydrometallurgical processing of the withdrawn PLS for production of value metal. The final step of the facility life cycle is the site closure, decommissioning and aftercare.

The review has been conducted at a time when the BIOMOre technology is still under development and being tested in pilot scale experiments in the Rudna mine in Poland. The siting, planning and design of a commercial size facility has not been started. Hence, the quantitative measures of impacts reviewed should be interpreted with caution, and the analyses presented in this report shall be regarded as examples rather than as a basis for judgement of the feasibility of the BIOMOre technology.

Another important aspect of the report was to demonstrate, that there was developed a consistent methodology in BIOMOre that allows to conduct an EIA for a real site using the tools and methodologies developed in the project.

Although the quantitative aspects of the EIA in this report remain uncertain, the study covers all vital aspects of potential environmental impacts from a potential commercial size application of the BIMOre technology. As such, this report can serve as a checklist for the work with the EIA in the licensing of a future ISR facility. Within the BIOMOre project, this report will be used in the next task of the environmental assessment that will involve a comparison between the impacts of a BIOMOre technology-based facility with conventional mining.
12. References


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