ITERAMS

H2020 ITERAMS
INTEGRATED MINING TECHNOLOGIES FOR MORE SUSTAINABLE RAW MATERIAL SUPPLY

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INTEGRATED MINING TECHNOLOGIES FOR MORE SUSTAINABLE RAW MATERIAL SUPPLY

RELYING ON THE ITERAMS PROJECT LIBRARY OF DELIVERABLES, PUBLICATIONS, AND CASE STUDIES BY THE WHOLE TEAM OF ITERAMS RESEARCHERS.

Edited by:
GreenDelta

2020, www.iterams.eu

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HOW IT ALL BEGAN.

IN 2017, THE ITERAMS PROJECT CONSORTIUM STARTED THE ADVENTURE TOWARDS MORE SUSTAINABLE MINING UNDER THE EUROPEAN UNION'S HORIZON2020 PROGRAM.

THE PROJECT MARKED A NEW DIRECTION TO THE MINING INDUSTRY IN RELATION TO MINE WATER AND TAILINGS.

ONE OF THE MAIN CHALLENGES OF THIS CENTURY IS TO CONSERVE AND PROTECT FRESHWATER.

No matter whether in water scarce or in water abundant areas, water is a critical issue for all mining companies and nearby societies. The scope of ITERAMS is to radically reinvent the role of water and waste in mining and to transform the current environmental challenges from a liability into an asset. Water and waste are valuable resources, which must be reused in the mining industry.

Three and half years later, we have accomplished great results, which are summarized in this book. We have exciting news how the water loop can be closed at the mine sites and which aspects need to be considered.

Water technologies, on-line sensors, ore sorting and new approaches to the valorization of tailings have been piloted at mine sites in Finland, Portugal and South Africa. These campaigns have demonstrated that new sensors can reliably monitor contaminants of interest and water can be cleaned efficiently and made 'fit-for-purpose'. Real value has been shown with ore sorting, with rapid adoption in the mining industry expected. Dry tailings have been transformed into a cement like material in a process called geopolymerisation. We have developed a protocol on closed water loops with clear recommendations for all stakeholders, building on the knowledge created during the project.

The closed water system is complex, requiring expertise from various disciplines and organizations. This book is the result of fruitful cooperation between 16 partners from industry, research organizations and universities across EU member states, Turkey and South Africa. I am particularly delighted to see the enthusiasm of our industrial partners in applying the successful research and development results at their operations. I trust that the ideas of this book will be useful and further adopted by mining and technology companies worldwide.

Water and waste can be a business case for the companies and at the same time improve the overall performance of the mining sector.

Päivi Kinnunen
ITERAMS Coordinator
VTT Technical Research Centre of Finland

1 WATER AND WASTE ISSUES IN MINING – AND THE BROADER QUESTION OF SUSTAINABILITY

STARTING POINTS FOR THE ITERAMS PROJECT

Since prehistoric times, mankind has mined valuable materials from the Earth, and it will remain essential for accessing metals and other materials for the foreseeable future. Mining has a reputation tarnished by its historical environmental performance, its consumption of water and energy and its handling of waste. Going forward, mining must change and focus on delivering the metals and minerals needed for the world with a strong focus on sustainability.

MINING IMPACTS

Mining activities, from exploration to operation to decommissioning of mines, have a multitude of effects; in the past, mining has changed entire landscapes. Effects include use of local resources (e.g. land, water), release of harmful emissions, directly from the mine operation or from tailings remaining from the mining activity, traffic and noise, but also positive impacts on the local economy for example. Mining has also social effects, from the workers in the mine to changes in the local community. Often, today, mines are criticised from society and local community, which is often summarised in the question whether a mine has a social license to operate, SLO. Effects can be attributed to the normal activity of the mine, such as the withdrawal of a certain amount of water per ton of mined mineral, and also to accidents that only happen with a certain probability, but when they happen, might have more severe impacts. And of course, mines always have long term impacts, which last even after a mine is out of operation. All this calls for a complete and efficient assessment framework for understanding and managing the impacts of mining. The ITERAMS project expands a full sustainability and risk assessment to this end.

The ITERAMS project started with the idea of closing the water cycle at mines, striving towards zero effluent discharge with dry tailings storage facilities. Wet processing of ores delivers high water consumption, which leads to challenges in effluent handling and to availability issues in water-scarce regions. Only a portion of the untreated wastewater can be recycled because of its advert effects on the beneficiation process. The rest might be discharged, posing contamination risk and and incurring energy for treatment. Closing the water cycle in a new way promises to overcome both these two aspects.

Taking the tailings, the solid by-product of mineral concentration, it should be possible to generate products with concrete-like properties, which could be used to cover and stabilize surface storage facilities or used as underground mine backfill materials. Products could also be offered on the market or used within the mine for other purposes. Thereby, waste generated during the mining process can be turned into valuable products. Thus, the project was to study, test and refine the required technologies, and explore them under different conditions as case-studies at mine sites. Furthermore, to investigate whether they are indeed beneficial for the environment and add value from an economic and social perspective. Water quality changes over seasonal periods were studied at three mines; one in the arctic climate with freezing temperatures and heavy snowfall in the winter, and fast melting of snow in the spring (Kevitsa); one in a temperate region with seasonal rains and one in an arid environment (named Site B and C). The ore types and the related process flowsheets were also very different. A portfolio of treatment methods to adapt the recycled water properties to suit the process requirements was explored and tested. In all cases, the amenability of tailings for the production of different types of geopolymers was assessed. A full sustainability assessment was performed for the cases mentioned above. Initially planned for three years, the project was extended due to the CoVid “situation,” which slowed down laboratory work and also the validation work in the mines. Now, at the end of the project, it is good to present and discuss whether and how far this portfolio of new technologies indeed can lead to more sustainable mining, covering environmental, economic, and also social aspects, and addressing predicted impacts and risks.

This short book is to be seen as a higher-level summary: it aims to guide users from the initial challenges and ideas to the technical and conceptual results of the ITERAMS project. Readers interested in more comprehensive descriptions are referred to the detailed project reports available on the ITERAMS website´s download section.

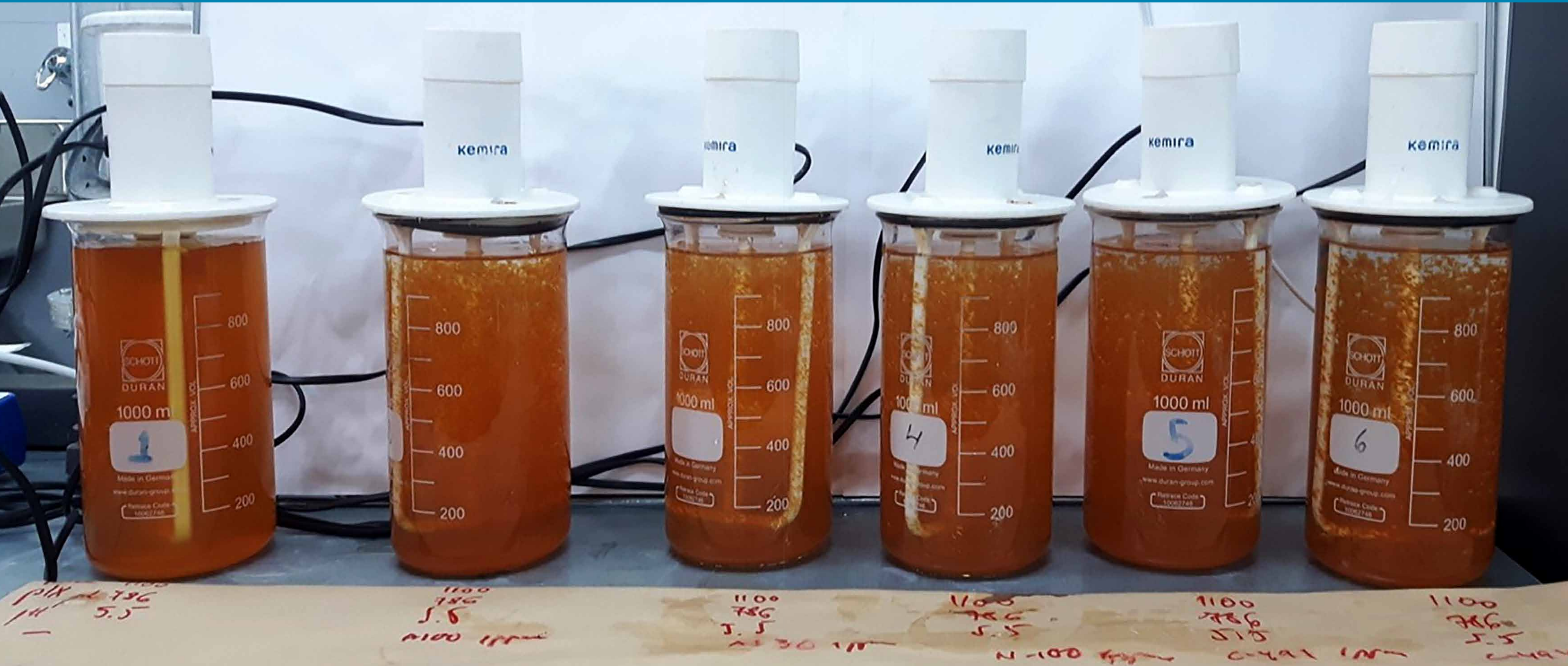
Project ambition and work plan fit obviously nicely to the Green Deal, and to the goal of ensuring access to resources for the European economy [1].

SUSTAINABILITY

Sustainability has evolved as overarching key term to describe and assess whether and how well civilisation and nature can coexist, and to address especially how much human activities affect this coexistence, in terms of environmental, social, and also economic impacts, in short and longer term. The 17 Sustainable Development Goals (SDGs) [2] from the UN were developed with the idea to make the broad concept of sustainability more operational; mining links to such diverse SDGs as climate action, clean water, life on land, responsible production, sustainable communities, and decent work. Withdrawing resources from the earth is an irreversible process, and thus it is especially interesting to investigate how sustainable mining is, and how its sustainability can be improved.

2 ADVANCING TECHNICAL SOLUTIONS TOWARDS AN ITERAMS PORTFOLIO

Water samples in jars during the on-site testing of water treatment technologies



ADVANCING TECHNICAL SOLUTIONS TOWARDS AN ITERAMS PORTFOLIO

Year after year, the mining industry generates 5–7 billion metric tons of tailings worldwide. They are mostly disposed of on surface. This can cause environmental and safety problems including serious water pollution arising from contamination of surface water, groundwater, and soils due to the leaching of heavy metals, process reagents, and sulphur compounds. Furthermore, the local water usage of the mining industry can be very high, even dominating [3]. For example, approximately 65 % of fresh water is used in mining operations in the arid Antofagasta area in Chile [4]. This does not only lead to a high dependence on available water stocks in the area of a mine but can also lead to conflicts with surrounding stakeholders.

Building on existing concepts and techniques, ITERAMS has refined, advanced, and tested a portfolio of technical solutions for closing the water loop for mine sites, and for generating useful products from water treatment and tailings as well. These will be described in this chapter.

TAILINGS

The term “tailings” is used in mining for describing the waste stream which is produced at mine plants, as a discharge of chemical and physical processes which are used to extract the desired material from the ore. It typically has a slurry consistency and consists of finely ground rock and process effluents.

2.1 ORE SORTING

Ore sorting targets the removal of non-valuable materials as coarse particles to avoid the processing of ore below the cut-off grade in the following mineral processing stage. This will prevent processing of material where the cost exceeds the value of the ore itself [5;6]. Consequently, ore sorting reduces the amount of the material to be processed in the next steps, which results in lower energy demand, less water and reagent consumption and a reduction of waste. These advantages become even more significant as the ratio of the excavated waste rock to valuable metals has increased over time [7]. Nevertheless, ore sorting has been ignored by mines for several reasons, such as the difficulty of measurement and material handling challenges [5].

ITERAMS aimed to prove that on-line analysis will detect low-grade ore with sufficient accuracy in lot sizes which could be sorted from the feed stream. This will improve the flotation performance and reduce the environmental footprint. Furthermore, the project provides an economic analysis of ore losses.

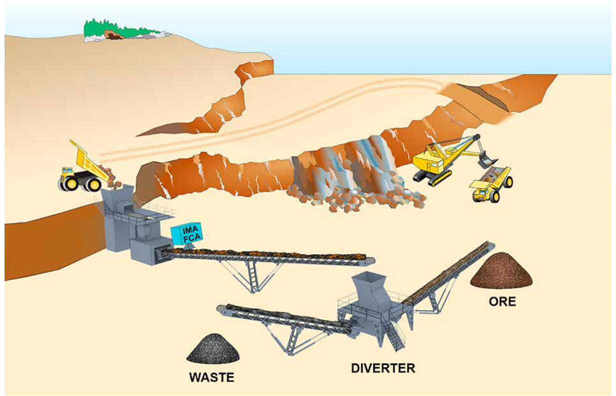


Figure 1. The basic idea of pre-concentration using bulk ore sorting methods to separate high-grade ore and low-grade, where the latter is considered as waste stream (© IMA Engineering)

To detect possible low-grade or waste materials, primary crushed ore was considered to reflect the inhomogeneous ore structures and grade variations. Measurements from crushed ore should be able to estimate the sorting potential of the mine feed. Hence, for technical reasons, an on-line sensor was installed on the main feed conveyor right after the primary crusher of the Kevitsa mine.

ABOUT ORE SORTING TECHNOLOGIES

There are two different sorting methods: particle sorting separates single particles from a stream, and bulk sorting separates partial lots from a continuous stream. The detection methods are based on the different properties of single rock pieces or on average properties of material passing by the sensor. The measurement can be done by mass (tomography) or colour (optical methods) or on-line spectral sensors (e.g., XRF, PGNAA, LIBS, LIF, RAMAN and IR). Even if the same sensor technologies can be applied, the bulk and particle sorting are fundamentally different and have different strengths and weaknesses. Bulk sorting can be performed from a few to thousands of tons per hour without technical or economic limits. Data from sensors need to be gathered for a time that depends on the sensor configuration. The mass that passes during the signal gathering time is the smallest mass unit which can be separated with a flop-gate or diverter chute. The gathered value is an average over that mass. The method is efficient to remove gangue fractions from the feed stream.

Particle sorting is more complicated because it requires particles in a narrowly sized band for analysis and removal by compressed air jets. The technology allows the use of several sensors at the same time. The method can give high recoveries in sorting. The selection of a sorting method is usually decided case-by-case, which reflects the uniqueness of each deposit and raw material feedstock.

ANALYSIS RESULTS AT KEVITSA

The material from the samples which had been collected at the sulfidic mineral mine in Kevitsa, Finland was analysed with the XRF sensor. Figure 3 & 4 show the results of the ore sorting campaign. The ore loss ranges between 5 % and 10 % at contact, and as the waste quality is not known, some sulphide waste is piled wrongly in the inert waste area. This latter case may eventually lead to contaminated water leakage in the environment. Furthermore, in this preliminary study, it was possible to identify the hard rock minerals using the LIF method and to detect talc minerals using LIF and IR methods. Besides, the best on-line option to analyse light elements at the conveyor was determined to be the PGNAA method even though it is slow.

Figure 2. Material samples collection at Kevitsa

The data from Kevitsa was further used for analysing the economical bulk ore sorting potential, should the waste material be sorted from the mine feed. Economic calculations can be done to estimate how much below cut-off ore can be sorted, and how much higher ore grade resides in the feed. This was done by setting an estimated economic cut-off level to the collected data, to calculate how many tons in the feed fall below the economical cut-off level. The virtual calculation is based on diverting the material below the cut-off level to the side, and by replacing it with average grade ore. In Kevitsa, the potential for the increased value was calculated to be more than 10 Million Euro annually.

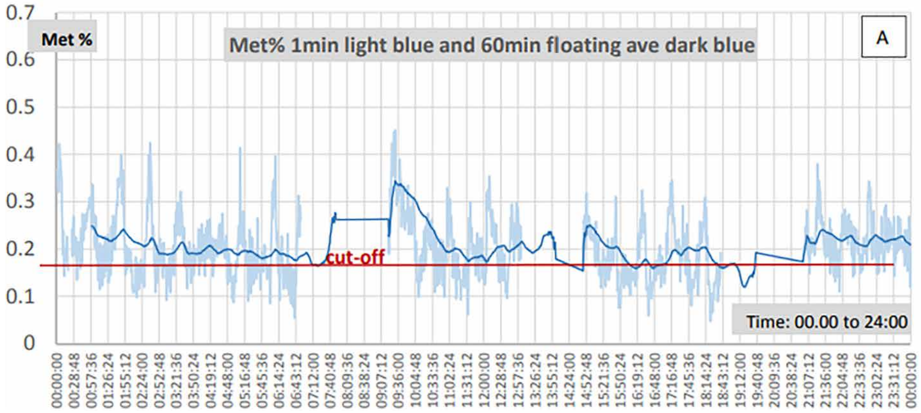


Figure 3. The study on metal content (%) during 24 hours shows 1 min (light blue) and 60 min (dark blue) floating average rate from primary crushed ore [8].

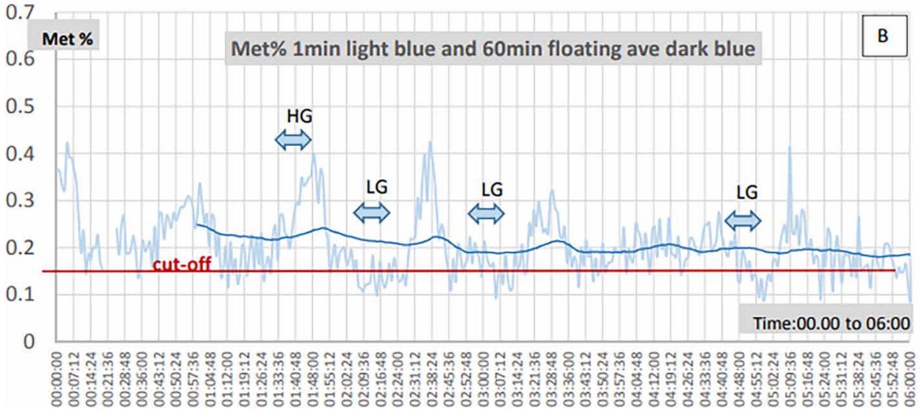


Figure 4. During 6 hours in the morning, 3 truckloads could have been sorted, representing about 10 % of the total feed (1 load of high-grade ore HG, 3 loads of low-grade ore [LG]). The arrow in the figure shows approximately the time in which one of those truckloads is processed in the primary crusher [8].

2.2 VALORISATION OF MINE TAILINGS

The ITERAMS project also studied if the gangue rock in the participating mines could be used as raw-materials for useful geopolymer products. The tailings of many existing mining operations contain the aluminosilicate minerals needed for alkali-activation, at least to some extent. From a sustainability perspective it makes sense to use solid alkali-activated products, which are generated from tailings directly at the mine site as

1. backfill material applied to fill open stopes from the (underground) mining operation and
2. cover materials for surface deposits of tailings to store them ecologically safe and sealed off from the environment.

To understand the process of geopolymerisation, one needs to take a look at what happens when a solid material gets in contact with a liquid solution: If for example aluminium or silicon is present in the solid, an alkaline solution can dissolve these elements. The relative amount of dissolved species depends on the stability of the solid phase in which the specific element is incorporated. As an example, silicon dissolves relatively easily from a glassy structure, whereas it is almost insoluble in the form of quartz with its three-dimensional network structure. Therefore, besides the chemical composition of a material, the mineralogical composition is crucial for the dissolution of certain species in alkaline conditions. Furthermore, the particle size and the particle composition play a crucial role. In the end it comes down to a simple question: Which mineral phase is in contact with the liquid solution?

In mine tailings, most of the fine particles are made up of several minerals and only some consist of just one mineral (see Figure 5). Whenever a mineral phase is not at the surface of the particle, it will not be in contact with the solution. Therefore, this specific phase will be inactive with respect to dissolution unless the surrounding material is dissolved. The amount and ratio of especially aluminium and silicon in the solution govern the structure of the precipitates formed and consequently have a significant influence on the properties of the resulting alkali-activated material. It is, therefore, crucial to know the contribution of certain minerals in tailings to the number of dissolved species in an alkaline solution.

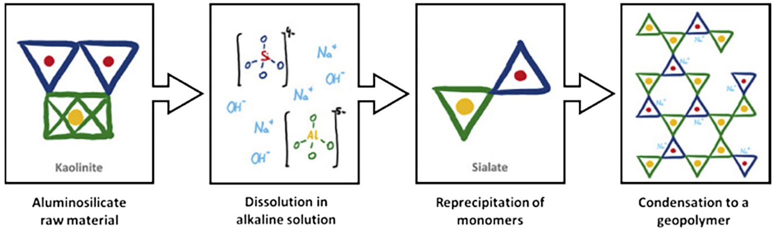


Figure 5. Simplified illustration of geopolymerisation of an aluminosilicate raw material. An alkaline solution dissolves Aluminium and Silicon ions that have a tetrahedral coordination in the solution. When the solubility limit is reached, aluminosilicate monomers precipitate and subsequently condense into more complex structures to form a solid network structure in the end.

The material samples from the mines were analysed, using the QEMSCAN (Quantitative Evaluation of Materials by SCANning electron microscope) method (see Figure 6). Unfortunately, QEMSCAN is a rather complex evaluation method and involves a lot of experience and time. Therefore, as an alternative and simple route, a series of direct dissolution experiments have been performed to establish a link between the chemical and mineralogical composition of certain tailings and the dissolution behaviour of crucial elements.

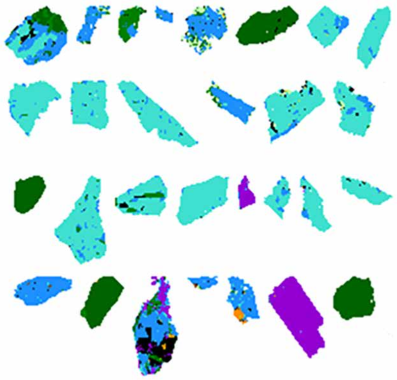


Figure 6. QEMSCAN results of a sample of mine tailings showing the distribution of different minerals in fine particles with a particle size between 75 and 106 µm. Each colour represents a different mineral phase; those that are not on the surface will not be in contact with a liquid solution.

The results of the dissolution tests were used to facilitate the mix design for alkali-activated products. Different known approaches were tested to increase the mechanical strength of the final product: the addition of reactive materials (e.g. blast furnace slag), increasing the reactivity of the tailings by grinding, and increasing the reactivity by curing at elevated temperature. Depending on the tailings type, the mix design, and the curing conditions the final material shows a compressive strength in excess of 30 MPa even for curing at low temperatures. Many successful products could be developed without any further treating of the tailings making this approach also feasible from an economic point of view.

The resulting alkali-activated materials are best used directly at the mine site, since further valorisation as e.g. construction material might be uneconomic due to the distance of most mining operations to potential end-consumers. Primary possible applications of such materials are therefore backfill for underground stopes and surface covers for tailings or waste rock storage facilities.

Within ITERAMS different on-site applications were developed according to specific needs of different mine sites:

1. Alkali-activated underground backfill material based on mine tailings to replace traditional cementitious backfill. This avoids using cement as the binder and additionally increases the amount of tailings that can be deposited underground. Consequently, the amount of tailings to be stored in surface deposits is reduced and possibly the mine life can be extended.
2. Surface cover for high sulphur waste rock and tailings. This cover layer can be made watertight and therefore no surface waters (especially precipitation) can get in contact with the material underneath. Consequently, the potential formation of acidic drainage is restrained and these covers act as an environmental protection layer.
3. Dust reduction layers for surface tailings deposits. During sunny weather, the evaporation of water from surface deposits of tailings increases dust formation. This is a constant problem in arid areas but also present in the arctic during its short summer. Alkali-activation was investigated and successfully tested to form a surface layer that has a higher resistance to dust formation. As a result, the tailings are not spread by wind and the environmental impact is reduced to a minimum.

The properties and performance of the resulting solutions have been evaluated in lab experiments, especially concerning their long-term stability to the local needs. For example a surface cover installed in the arctic has to be able to resist and survive freeze-and-thaw conditions. Additionally, for some applications, it was possible to perform on-site field tests to confirm the results of the lab experiments under real conditions. To assess the long-term stability of these materials, simulation models have been developed based on the local conditions and the properties of the resulting materials.

VALIDATION OF APPLICATION SCENARIOS

The described scenarios were further developed based on individual needs of specific mine sites and in accordance with the potential from the available tailings, especially for direct use without further intensive processing. As a result, the following possible applications were intended and tested in small-scale demonstration pilot tests to evaluate their suitability and performance:

- Cover for high-sulphur waste rock and tailings
- Underground backfill to replace cementitious backfill
- Dust reduction system

The testing for underground backfill and for the dust reduction system couldn't be performed at the specific mine sites but was carried out under appropriate conditions elsewhere. The cover scenario for high-sulphur waste rock was implemented directly at the Kevitsa mine. Here, different recipes for cover scenarios were tested at small scale on a horizontal and on an inclined surface to mimic the intended real-life application and subsequently evaluate their performance under realistic conditions.

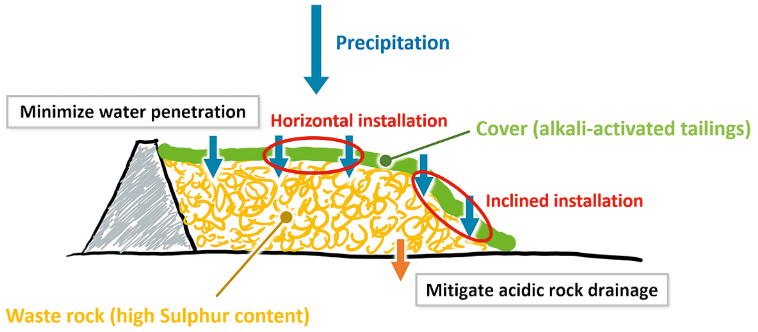


Figure 7. Cover scenario on high-sulphur waste rock to minimize water penetration from precipitation and consequently mitigate acidic rock drainage. This setup was rebuilt in small scale to evaluate possible installation methods and allow for the further monitoring of the performance of the covers.

Figure 7 shows the basic principle of the cover installation on high-sulphur waste rock. Five different recipes were prepared to have a pumpable consistency to allow for the installation in large scale by state-of-the-art construction technologies for pumped concrete. Two different inclinations were successfully tested (Figure 8). The horizontal installation was performed in a similar way. Additionally, a surface pool was installed to allow for accurate water penetration testing. These covers were also subjected to freeze-thaw cycles to mimic the climatic conditions at the mine site (Figure 9). Water penetration as well as surface and drainage water composition will be further monitored even after the end of the ITERAMS project to evaluate the mitigation of acidic rock drainage over a more extended period.

Figure 8. Installation on inclined surfaces of waste rock at two different angles. The cover recipe was applied at the top end of the inclination.

Figure 9. Horizontally installed cover on high-sulfur waste rock. The surface pool was filled with water and then exposed to the outside conditions (temperature up to −16°C) to simulate freeze-and-thaw cycles.

First results prove the freeze-and-thaw resistance of the covers and already indicate their positive effect on water penetration and acidic rock drainage. A cover scenario using the plain tailings without alkali-activation does not reduce the water penetration. Only when alkali-activated covers are used, the water penetration can be limited and consequently mitigate acidic rock drainage. Additionally, a specific strength of the cover is required to withstand freeze-and-thaw conditions.

The tests of the alkali-activated backfill scenario showed the suitability for underground installations. Based on presently available results a superior performance compared to the normally installed cementitious backfill can be expected especially for long-term performance.

2.3 WATER TREATMENT TECHNOLOGIES

At a mine, waters of very different physical properties and chemical compositions are managed. These include various primary water sources (natural surface and underground waters, cleaned sewage water) and recycled waters (pit drainage, site runoff; thickener overflows, tailing pond returns). A prime objective of the ITERAMS project was to isolate the process water circuits wholly from adjacent water systems. The reduction of freshwater uptake and mitigation of the risks of contamination of fresh surface or ground waters with mining effluents will follow. However, this technical isolation of the mineral processing plant relies on the implementation of closed loops across the various process water circuits of the mining operation.

Closing the water circuits without cleaning may affect the overall plant performance because of the accumulation of compounds. It can cause recovery losses or decreases in product quality. It may also increase the plant's maintenance costs because of gypsum formation. These effects are more pronounced for processes with short water circuits, e.g. recovering most of the water from tailing thickeners. Residence time becoming very short compared to the kinetics of reactions in water will introduce thermodynamic instabilities. In processes with water remaining in tailing dams for long periods, the chemical reactions had time to balance. This basically means that a new and different dynamic, multi-component system is created. If not monitored and controlled appropriately, it will result in a loss of information about the whole operation, and hence, a loss of control over the plant performance. – Therefore, water management needs to be reinvented. This led to the following research questions for this project:

1. Can the water compositions be modified to allow water reuse in various unit processes of the plant?
2. Which substances are the most critical or beneficial to the recovery of specified minerals?
3. What are the acceptable values for the impurities in the recycling loops?
4. Which water treatment technologies may reach the acceptable values of the contaminants?
5. How to measure impurities in the process on-line, in real-time, and at a reasonable cost?
6. Can the final balance of a fully recycled water system be modelled and estimated?

FIELD SURVEYS TO DETECT CRITICAL COMPONENTS IN WATER

The three mines in the ITERAMS project provided access to their mine site to conduct field surveys (Figure 5). As said, they exploit polysulfide deposits with different mineralogy. They also differ in make-up water quality and availability. The surveys consisted of sampling water and slurry streams inside and outside the plants. Their chemical and microbial properties were analysed at third party laboratories. Additionally, the historical exploitation data from the mines were investigated through multivariate statistical analysis. The aim was to tease out the most influential factors on the plant performance, in terms of recoveries, grades and selectivity of the mined minerals. Alongside this, the feedback from the industrial mining partners was also sought.

Lastly, the kinetics and trends of accumulations of different substances when the waters are recirculated in closed-loop were investigated through a dissolution protocol designed explicitly during the project. The protocol quantifies the potential of a given ore to release its elements into the water, during the comminution or the flotation operations.

FLOTATION

Flotation is a wet processing technique where small gas bubbles attach to and lift fine particles to the top of the vessel (flotation cell) for collection as a froth. Most of the minerals do not naturally adhere to gas bubbles. They are hydrophilic. The attachment is controlled by making the surfaces of the wanted mineral particles hydrophobic, which will allow the bubbles to attach. The change is made by adding chemicals called collectors to the pulp. Collectors have a specific property to stick both on a mineral surface and on a gas bubble. These chemicals can be made to selectively adhere to the elements of a specified mineral surface. The selective adsorption is affected and controlled by modifications in the water chemistry; its pH, ORP, OD etc. Several of the collector chemicals have adverse effects on the environment even at quite small concentrations in effluent waters. [9].

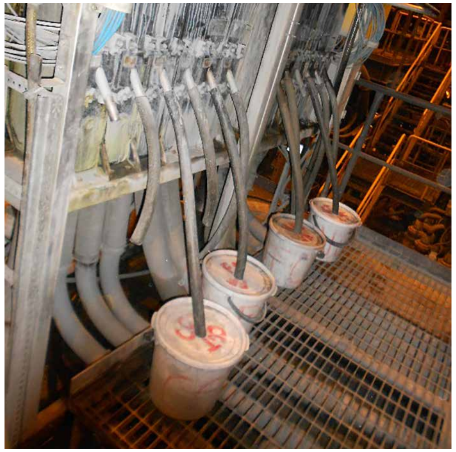


Figure 10. Illustration of sampling surveys: sampling effluents in the process plant

The results of the surveys, the feedback from the industrial partners, the historical data analyses, and the estimations of ionic accumulation in recirculated waters allowed to identify several ions (Ca, Mg, NO_3, SO_4, S_2O_3 ...), colloids and some microbial populations as the critical components for flotation, all indeed typical for mines with different sulphide ore types. This leads to the question of why these components are seen as contaminants, in simple words, why are they bad.

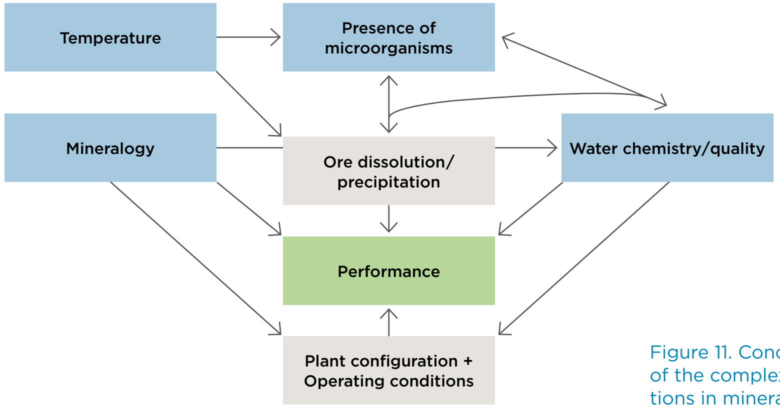


Figure 11. Conceptual view of the complex interactions in minerals flotation

Effects of these ions on sulphide mineral flotation have been studied before but mostly as single laboratory test variables. The difference in ITERAMS was to learn also their interactions and combined complex responses in industrial environments.

Figure 6 depicts the essential interdependencies. Advanced mathematical methods were used on obtained data-sets to estimate the water variable correlations with operational and mineralogy changes.

To investigate the causal water relations scientifically, the effects of these critical components were also studied at a laboratory scale at mine-sites with local waters. Much effort was used to research sulphur compounds such as tetrathionates, dithionites, thiosulphates, and sulphate for their effects on flotation as part of the water property matrix.

It was clearly shown that in general, the presence of the thiosalts resulted in poor flotation performance of some minerals. More detailed results of these studies are specific to each site. They can be found in the deliverables and the publications produced during the project. However, due to the recirculation of process water, the accumulation of such contaminants is inevitable. Therefore, keeping their concentration at a level where the process performance is not affected is necessary and can be achieved with different water treatment technologies.

INVESTIGATED WATER TREATMENT TECHNOLOGIES

Several treatment technologies with the potential to decrease the concentrations of the previously identified components were considered for the studies in ITERAMS. They aim to remove or reduce:

1. colloids, by a sequence of coagulation/flocculation of the suspended solids followed by the sand filtration of the flocs, or
2. dissolved species, suspended solids, colloids and microorganisms by dissolved air flotation (DAF), or
3. dissolved species and microorganisms by ion-exchange resins (IER), or
4. dissolved species by electrocoagulation.

Most attention was paid to the DAF and IER, possibly using the other methods (sand filtration, electrocoagulation) rather as supplementary technologies for a more comprehensive treatment of all components in the process waters in the future. For this reason, coagulation/filtration, as well as electrocoagulation, are introduced shortly.

The coagulation/filtration process was developed and tested at the laboratory scale (Figure 12). The work included the selection of the best flocculant and the optimal conditions to reach the lowest turbidity of the waters. The study confirmed that flocculation is an efficient operation to decrease the colloids in waters, by promoting the agglomeration of particles into dense flocs more easily separable. Subsequent filtration through a composite material removed the flocs and decreased the concentrations of the chemical reagents used during the flotation of ores by more than 85 %. This process is efficient in improving the quality of the water.

TURBIDITY

Turbidity was repeatedly used as an optical quality indicator for water samples during the project. It describes the haziness of a fluid caused by tiny solid particles, which scatter light, similar to smoke in air. It´s usually reported in nephelometric turbidity units (NTU).

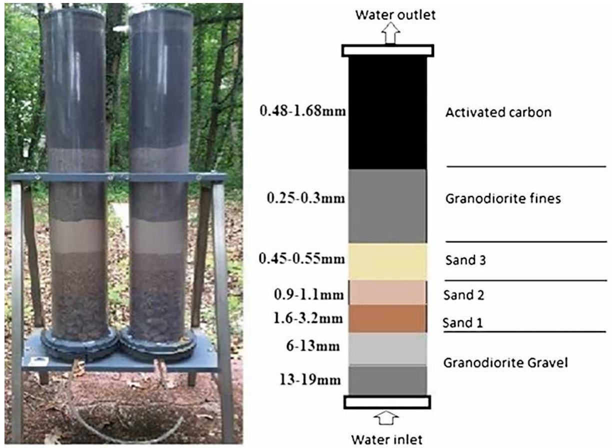


Figure 12. Experimental setup for the removal of suspended solids by sand filtration (after flocculation)

Additionally, electrocoagulation tests were performed to precipitate thiosulfate and sulfate from synthetic waters into a solid form that can be removed by filtration. The tests were conducted in batch and continuous configurations, using Fe/Al electrode pair. The removal of thiosulfate reached 90 % in 5 hours of an experiment at pH 8 and with a current density of 3 A.

VALIDATION OF THE ION EXCHANGE RESINS

VALIDATION OF TECHNOLOGIES

Validation is a big promise, and it makes sense to clarify how we use it in the context of ITERAMS. For the water treatment technologies, and also the use of alkali-activated materials and geopolymers, the validation work aimed to evaluate if reproducible performances could be obtained, using at least small-scale on-site tests. Furthermore, it included a continued verification, i.e. the evaluation of the technology and involved processes remain in a state of control, also under changing conditions.

Two water treatment methods, dissolved air flotation (DAF) and an ion-exchange resin (IER) were selected to demonstrate their applicability for removing the critical components on-site. The studies for the IER consisted of two steps: (1) the adsorption studies on a laboratory-scale, which the researchers used artificial process water samples for, and (2) the validation studies with process water from Site B and the Kevitsa mine.

ION-EXCHANGE RESIN (IER)

Ion exchange is the reversible interchange of ions between a solid and a liquid such as water. A resin, or alternatively a polymer, built as an insoluble matrix, acts as the medium which captures (unfavourable) ions from the liquid and in exchange releases other ions to the solution [10].

The objective of the laboratory studies was to gain more knowledge about various types of ion-exchange resins, and how they perform particularly concerning the removal of sulphates and thiosulphates. Beyond that, the work consisted of the determination of multiple parameters such as the surface conversion of the resins, their adsorption capacities, or the effective contact time between the resin and contaminated water. Furthermore, it was tested how the regeneration of a resin could be performed. This is necessary as the resin is only able to absorb a limited number of sulphates, which means that the adsorption capacity must be restored constantly (see Figure 13).

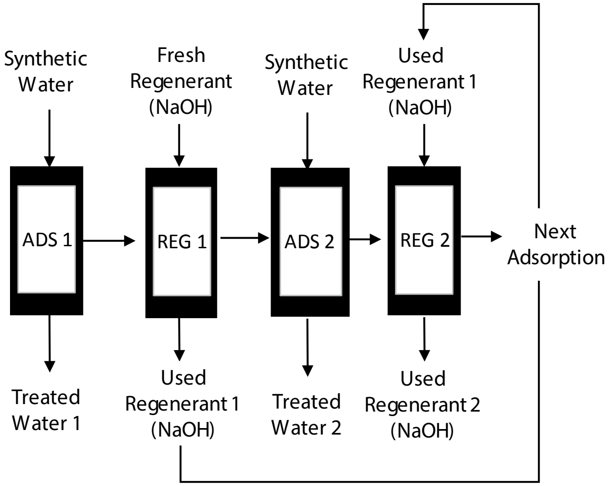


Figure 13. Schematic view of adsorption and regeneration experiments

The laboratory batch scale tests showed that a gel-type, strong basic, Type II anion resin is suited for the removal of sulphate and thiosulphate ions as well as residual organics from the process water. The test was conducted with a water flow rate of 4.5 L/h and 0.2 kg of resin. Based on these insights, a commercial resin was selected for further testing, and subjected to further treatment of its surface. The final tests with synthetic water provided optimistic indications that the sulphate level could be significantly reduced to 1000–1500 mg/L from approximately 3500 mg/L in less than one hour of adsorption period.

The insights were subsequently validated at surveys directly at Kevitsa and Site B, using large-scale ion-exchange columns (1.3 kg for a water flow rate of 30 L/h). The studies again included investigations on the adsorption potential, this time with real water streams from the mines, considering different flow rates. As the regeneration process accumulates a significant amount of sulphate ions in the regeneration solution which make reuse or safe disposal impossible, a separate test program for removing excess sulphate was conducted at Site B, applying ettringite precipitation.

The findings from this on-site work show that water treatment using IER indeed has potential for successfully decreasing concentrations of sulphates, thiosulphates and polythionates in process water of the investigated flotation plants. Approximately 60–70 % of sulphate and almost all thiosulphfate ions could be removed by strong base-type resin from the process water. In addition, IER decreased microbial numbers with an average of 86 %. Thereby, it is important to note that the flowrate of water had a significant effect on the performance of adsorption. As the composition of process water could be different for each mine, the required contact time between the resin and water components should be optimized for each case.

Also, it is possible to regenerate the resin using an alkaline solution so that it can repeatedly be reused for water treatment purposes. The regenerant solution can be used continuously but requires constant addition of fresh sodium hydroxide to increase hydroxide concentration in the solution. For removing excess sulphate from the regeneration solution, ettringite precipitation tests showed that more than 70 % of the sulphate ion was precipitated as ettringite and the same regeneration solution could effectively be used for resin regeneration.

VALIDATION OF DISSOLVED AIR FLOTATION

Not like IER, which is – standing alone – unable to remove colloids, DAF was found to have the potential for removing any kind of identified critical components. At the same time, it could be used as a pre-treatment step before the ion-exchange treatment to avoid contamination and blocking of the ion-exchange resins by fine suspended solids. Both aspects were tested during the project.

DISSOLVED AIR FLOTATION (DAF)

The DAF principle is simple: it relies on the use of fine bubbles that are created by dissolving air in water under pressure and subsequently releasing the air to atmospheric pressure in a flotation basin. Chemical reagents are dosed, that precipitate and agglomerate the different dissolved substances and fine suspended solids, bacteria and colloids present as contaminants in the water, and form so called flocks. The fine bubbles attach and engulf inside the flocks and raise to the top of the basin carrying the contaminant with them from where they are removed (Figure 14).

Figure 14. Validation at Kevitsa with pilot DAF test container (35000 L/h). The orange and black sludge floating on the water surface comprises the impurities removed from the water.

In the first stage, again, laboratory testing with synthetic process waters formulated based on the water quality data from the mine sites was performed, following a similar approach at both sites: After having selected an appropriate water volume sample for the analysis, physico-chemical characteristics such as temperature, pH, ORP, conductivity, turbidity and dissolved oxygen levels were measured for each sample. In the following, before investigating the actual DAF treatment, the research team screened the optimal coagulant/flocculant chemistry, e.g. which pH to choose or which coagulant and flocculant to use. For the last step, it was important to choose a flocculant that produced flocs that were light enough to be lifted by the fine bubbles, but strong enough to withstand the turbulence created during the DAF process (Figure 15). The DAF experiments were then performed in a 10 L custom build column (Figure 16). The efficiency of the coagulation/flocculation and DAF process was evaluated on-site based on the change in turbidity between the initial sample and the sample obtained after the treatment process and later on from the water analysis results obtained from the analytical laboratories. The treated water was finally used for laboratory flotation tests.

The experimental work posed some challenges due to the complexity of the contaminant matrix. It was found that even the certified and accredited analytical laboratories had difficulties in analysing the complicated water matrix consisting of inorganic and organic compounds and bacteria which means that the accurate evaluation of the experimental data was very challenging and sometimes impossible. This was one of the most significant challenges encountered during the experimental work. For specific water streams, very high reagent concentrations (over 5x the usually required concentration) were needed to achieve adequate removal of the dissolved and suspended species.

Figure 15. Flocs in the laboratory DAF column before the fine air bubbles are introduced into the column

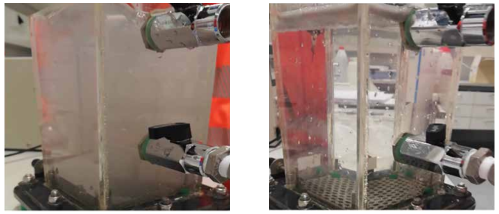
Figure 16. DAF experiments in laboratory column at Site B (left) and Kevitsa (right)

The continuous DAF validation was done by taking the feed water for treatment directly from the plant´s process water circulation and using it in small-scale pilot test containers (Figure 14). Due to the vast water flowrates (~10 Mm^3/a) of the minerals processing plant, the continuous pilot-scale equipment could only treat a small fraction of the total water flow. This marginal treatment could not yet cause any changes to the plants' flotation performance. Consequently, laboratory-scale flotation experiments were still used to prove the effect of treated water on flotation performance (Figure 17). While the work at Site B was performed in 10 L columns, the test containers at Kevitsa allowed for treatment validation at a pilot-scale test container, capable of treating 35 m^3 of water per hour.

At Kevitsa, the first results confirmed that DAF enables efficient removal of non-settleable fine solids and microorganisms from the plant water. Advanced oxidation, which has been simultaneously tested, was found to have significant potential to enhance the efficiency of sulphur oxyanion oxidation.

Figure 17. Outotec GTK LabCell for laboratory flotation tests (left), and concentrates (right)

This may indicate a substantial decrease in treatment costs. Optimized experiments show that DAF reduces plant water turbidity values from the initial level of ~200–300 NTU down to 4 NTU, which is a significant reduction. A noticeable decrease in bacterial marker gene counts was also achieved. Additionally, the validation confirms that treatment result obtained in laboratory conditions (Figure 18a) can also be achieved in a continuous pilot scale. The DAF process remains in a state of control even under dynamic production conditions where the quality of the feed water changes continuously (Figure 18b). The results for lab-scale mineral flotation experiments also confirm that the treated water has a positive impact on flotation recoveries. However, due to considerable variation in feed water quality, continuous control of DAF operating parameters is required to ensure adequate treatment performance.



a) Lab scale

b) Continuous pilot scale

Figure 18. On-site DAF validation. a) Laboratory-scale experiments; feed water (left) and DAF treated water (right) b) Continuous pilot-scale experiments; feed water and treated water quality

At Site B, the experimental results show that water purification consisting of coagulation/flocculation combined with DAF treatment can remove up to 99 % of the bacteria, and suspended solids to over 96 % when the initial turbidity was high if optimal chemical and process conditions are selected. Nevertheless, the concentration of the targeted thio-compounds has not decreased significantly during the treatment. The flotation performance results however did not show significant differences (Figure 19) when performed with treated and untreated waters. When considering these results in conjunction with the laboratory flotation results conducted in synthetic process waters, we can conclude that even though DAF is very efficient in removing solids, in the two studied systems these solids most probably do not have a substantial effect on the flotation performance. This observation is contrary to results from Kevitsa site tests, where removal of fine solids showed marked improvements in flotation performance.

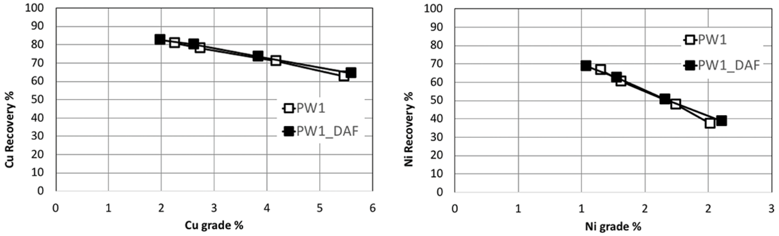


Figure 19. Copper and nickel grade vs recovery in the flotation tests with treated and untreated water

To improve flotation efficiency compromised by water quality, other water treatment technologies need to be tested that target these compounds. Nevertheless, as the flotation behaviour of every ore is different, for ore types where the presence of fine solids and bacteria has a detrimental effect on floatability, the coagulation/flocculation in conjunction with DAF can be a feasible water treatment solution.

VALIDATION OF WATER TREATMENT TECHNOLOGIES ON THE REMOVAL OF MICROORGANISMS

The previous results have shown that different water cleaning techniques also removed microorganisms to a varying degree. The performance of DAF was related to suitable water pH and aiding reagents (coagulants). This was considered as a noticeable reduction in bacterial marker gene counts depending on the process optimisation procedure. The best performing experiments showed a decrease in bacterial target gene numbers from 107 down to 105 copies per mL (99 % decrease), which may have effects on the process performance. However, despite the seemingly efficient removal of microorganisms (up to 90 %) with the tested water treatment techniques, significant numbers of microorganisms still remain.

2.4 SENSORS FOR WATER STREAMS

On-line monitoring of water quality from various sources in a mine site is a prerequisite for sustainable mine site water management. As Ca^{2+}, SO_4^{2-}, and $S_2O_3^{2-}$ ions were found to be some of the major ions accumulated in process water based on the water chemistry measurements, the development of appropriate sensors focused on these ions. Their concentration has generally been measured off-line in laboratories and the results have been reported after one day at best. Therefore, the aim was to develop a prototype for an on-line measurement system and electrochemical sensors for monitoring Ca^{2+}, SO_4^{2-}, and $S_2O_3^{2-}$ ions in water streams in a mine site.

Several probes were developed (Figure 20), all based on ion-selective electrodes (ISE), owing to their good mechanical strength and the absence of the liquid junction. The compositions of the electrodes are:

- for Ca^{2+} : carbon-based and polymer-coated electrode;
- $S_2O_3^{2-}$: gold-plated stainless steel electrode or Ag/Ag_2S electrode;
- SO_4^{2-} : hydrotalcite-based electrode;
- SO_3^{2-} : Ag/Ag2S electrode.

Lastly, Sb_2O_3/Sb electrodes were developed to monitor pH in the flotation waters.

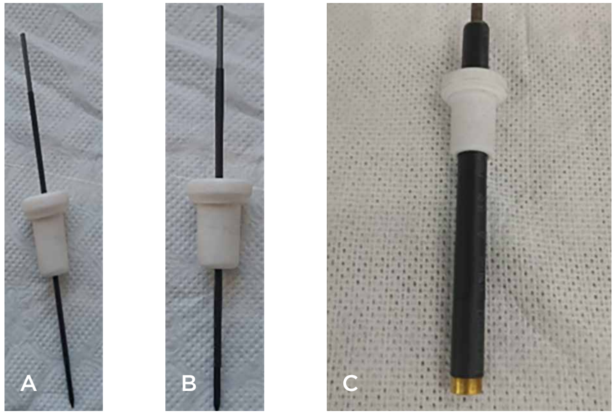


Figure 20. (A) Ca_2^+ ISE and (B) SO_4^{2-} ISE (Pencil graphite electrode modified with ionophore), and (C) Au plated stainless steel (316L) electrode for $S_2O_3^{2-}$ determination

The respective sensitivity, repeatability, detection and quantification limits, and robustness of these electrodes were determined during the field surveys of the project. After preparing the electrodes, the electrochemical device was developed for on-site detection of Ca^{2+}, SO_4^{2-}, $S_2O_3^{2-}$ ions in various water streams circulated in the flotation process (Figure 21 and 22). The electrodes and the measurement system were tested at Site B using water samples from various streams (Figures 23). A comparison of the results taken from electrochemical measurement in the mine site and laboratory assay results showed that the on-line measurement of these ions was possible.

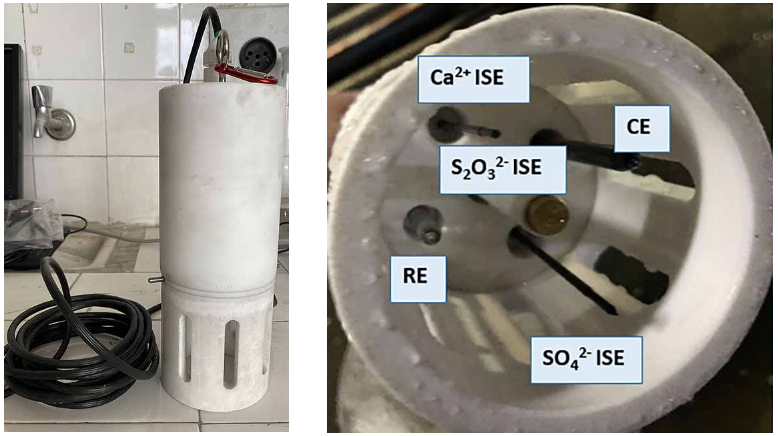


Figure 21 and 22. Electrochemical Sensor System

Figure 23. Long term Measurement of Ca_2^+, SO_4^{2-}, $S_2O_3^{2-}$ ions in ETAI stream at Site B

The results show that ITERAMS succeeded in preparing Ca^{2+}, SO_4^{2-}, $S_2O_3^{2-}$ solid-state Ion Selective Electrodes (ISE). The measurement techniques of these ISEs were significantly improved, using differential pulse amperometry (DPA). Their response was fast, and the surface cleaning was simple. Furthermore, it was found that the high sensitivity, good reproducibility, and excellent long-term stability make the new probe and measurement system a suitable device for on-line monitoring of water chemistry. These features were successfully tested for on-site measurements of sulphate, calcium and thiosulphate ions at Site B. The results obtained with Ca^{2+}, SO_4^{2-} and $S_2O_3^{2-}$ ISE were compatible with sulphate kit measurements and laboratory analysis. The on-site sulphate, calcium, and thiosulphate determination system became subject of a patent application in Turkey.

The sensors and the measurement system should now be tested for long term (several months) in various mine sites. Based on the findings from these tests, the sensors and the prototype could be modified and improved. A similar electrochemical measurement concept can be applied for the measurement of some other ions in industrial water.

2.5 MODELLING AND PLANT SIMULATION

Mathematical and numerical modelling allows to better understand what happens in the different steps of the beneficiation plant, including the relationship between the quality of waters and the processing performances.

The existing flotation models have been enhanced to consider the two main phenomena highlighted during the project: the dissolution of some minerals releasing ions in process water, and the impact of these ions and remaining fine particles on the concentration performances. In parallel, models have been developed for the water treatment technologies, namely the dissolved air flotation and the ion exchange resin. All these models have been introduced in a simulation platform, USIM PAC, and calibrated to better estimate the impact on the full plant of the observed phenomena at the scale of laboratory and pilot plant tests.

Plant surveys have been conducted for Kevitsa and Site B through several sampling campaigns at different periods to observe the seasonal variation of the water quality. For that, not only waters have been sampled, but also solids to estimate the metallurgical performances. Measurement results have been reconciled to obtain a coherent material balance. The analysis of the strengths and weaknesses of such procedures end in good practice guidelines for orienting the plant surveys towards water quality.

The simulator of the existing flotation circuit of the Kevitsa plant has then been calibrated to reproduce the observed performances (Figure 24). Based on the relationship between water quality and concentration performances obtained from laboratory and pilot tests, simulations have been performed to estimate the impact of process water treatment on the global plant performances and the results used in the frame of LCA to estimate the global advantages of introducing such technologies. The results are not always the intuitive ones coming from just laboratory tests, and further investigations will be necessary to verify the suggested plant behaviour.

Such simulation tool can be used for an existing plant to find the more appropriate technologies and configuration allowing an improvement of its performances and reduction of its environmental impact. But it can also be used for process design to consider, as soon as possible, the water quality, its seasonal variations, and its drift during the life of the mine.

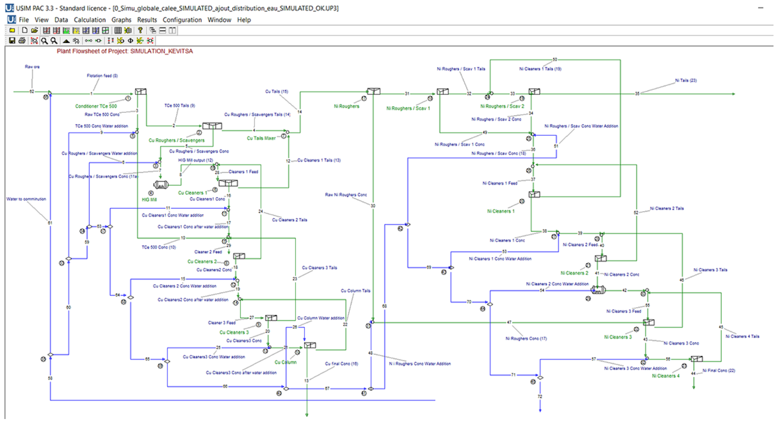


Figure 24. Flowsheet of the simulator of the Kevitsa flotation circuit

Water accounting is for the environmental impact assessment what metallurgical accounting is for the financial analysis. But both are interdependent and constitute useful tools for managing a mine site day after day. Indeed, water and metals are in contact from mine to port.

Traditionally, excepting hydrometalurgical plants, metal accounting is considering water just as the liquid to deduct from the total measured mass. The current project demonstrates the importance to consider water not only for its quantity but also for its quality. In addition, the water cycle goes over the metal routes, namely the tailings dams or pounds, the meteorological exchanges and land interaction, even with underground water. Manage metallurgical and water accountings at the same time is certainly the best way to take advantage of the full monitoring system.

The experience gathered during the project allows to propose guidelines for conducting an efficient water accounting in association with the metal accounting.

Flotation units at the Kevitsa mine,
with golden shining foam on the surface
(photo taken by A. Ciroth)

3 ADVANCING THE SUSTAINABILITY ASSESSMENT IN THE PROJECT

ADVANCING THE SUSTAINABILITY ASSESSMENT IN THE PROJECT

As already discussed in the preface, mining operations and related processes and products are multifaceted and complex topics. Assessing the sustainability of these operations requires approaches, tools and methodologies that can capture this complexity. Furthermore, when changes, e.g. novel technologies, are introduced on-site, a methodological framework needs to be set to evaluate the positive and negative aspects (impacts, risks) in comparison to the previous status.

A full sustainability assessment was performed in ITERAMS to investigate environmental, social and economic impacts and risks of the novel mining technologies introduced by the project. Specifically, the assessment aimed at evaluating if and how the ITERAMS solutions can (1) reduce environmental impacts and risks of mining operations in a life cycle perspective; (2) improve social performance of mines and trust and acceptance – the so-called "Social License to Operate"- of mining activities granted by local communities; (3) increase the cost-effectiveness of mining operations. The sustainability assessment was performed for two validation sites of the project, Kevitsa mine in Finland and Site B in Portugal. Qualitative considerations on sustainability were also made for a third validation site, Site C in South Africa, for which data could not be collected due to high confidentiality.

The sustainability assessment combined different qualitative and quantitative approaches for the diverse dimensions (environmental, social and economic) to tackle sustainability from different points of view and identify any burden-shifting from one dimension to another or within the mine life cycle.

A PROCEDURE FOR LIFE CYCLE SUSTAINABILITY ASSESSMENT

A step-by-step approach for performing a full life cycle sustainability assessment (LCSA) (see "Sustainability" on page 9) of mining processes and products was developed in the project (Figure 25).

The steps identified in the procedure can be grouped into three main areas: (1) preliminary analysis of the mining context to be assessed, (2) analysis and evaluation of the mining activities in the current status and when the changes (e.g. novel technologies) are introduced, and (3) use of a multidimensional perspective for the LCSA. All areas are finalized to the sustainability assessment.

PRELIMINARY ANALYSIS OF THE MINING CONTEXT

Conducting qualitative modelling is the first step recommended for the sustainability assessment. A qualitative, graphical model was created for ITERAMS by applying system thinking [11], [12] including substrates for the insulin receptor tyrosine kinase (IRS proteins, [13]). This model can be created in a fast and easy way; it highlights different variables, stakeholders and impact categories affected by the project and relations among them (Figure 26). This qualitative model was complemented by a sustainability hotspot screening which served to identify crucial issues and the main drivers for impacts in mining operations in general. Literature review and first interviews with key stakeholders, such as NGOs and mining experts, were conducted. In parallel, preliminary environmental and Social Life Cycle Assessment (E- and S-LCA) and Life Cycle Costing (LCC) were conducted, by analysing existing mining processes for Finland, Portugal and South Africa in well-established LCA databases.

For each site, it is important to have a clear picture of the context where mining operations occur. A study of the background situations, i.e. local situations, includes the definition of the socio-economic, social, environmental and governance conditions in the area. A review of the local circumstances will also enable the researcher to identify related stressors (such as tailings spillage, or water contamination) which represent pressures on the environmental, social and economic dimensions, hence potentially creating risks and impacts.

The results of the preliminary analysis are useful to orient the subsequent full sustainability assessment in terms of effort, goal and scope.

ANALYSIS AND EVALUATION OF MINING ACTIVITIES BEFORE AND AFTER NOVEL TECHNOLOGIES

Data collection is a crucial step for the creation of a mining life cycle (LC) model that reflects as far as possible site-specific conditions. Typically, primary site-specific data collection needs to be performed iteratively with the mining companies and complemented with secondary data. Primary and secondary data collected are used to create a LC model reflecting the current status of mining operations. In the model, site-specific data are then linked to background processes in available LCA databases to consider the supply chains.

The second round of data collection is needed to investigate how changes introduced by novel technologies on site affect the current status of the mining operations. Once the data for the expected changes on site have been collected, they need to be integrated into a second life cycle model starting from the first model for the current status. At this point, a comparison of environmental and economic impacts of mining operations before and after the implementation of novel mining technologies can be performed by choosing an impact assessment method. Life cycle models were created with an extensive primary data collection for two sites of the ITERAMS project, Finland and Portugal. Results of the LCA and LCC are presented in Chapter 4.

It should be noted that not all sustainability aspects can be covered by LCA and LCC. Therefore, in ITERAMS, LCA is integrated within other sustainability assessment methodologies.

LIFE CYCLE ASSESSMENT

Life Cycle Assessment is a technique for assessing the environmental and/or social impacts that occur during all stages of a product's life cycle. After having determined the goal and scope of a study, big amounts of data are collected for material and energy inputs, waste and emissions, or social parameters. These data are subsequently "translated" into different environmental and social impacts by assigning characterisation factors to every flow (impact assessment). Based on the collected data, the analysis can be complemented by performing Life Cycle Costing, which results in a full life cycle sustainability assessment.

A MULTIDIMENSIONAL PERSPECTIVE

Not only potential impacts, but also risks need to be taken into account for the sustainability assessment of mining processes and products. For this purpose, a hazard-pathway-receptor model was developed to investigate a potential mechanism of harm of a risk with and without the ITERAMS solutions. Furthermore, cause-effect relations between risks were investigated qualitatively.

Tailings emissions to groundwater are largely contributing to toxicity impacts – both on humans and freshwater – deriving from mining operations and are known to occur over periods of hundreds of years. A reactive transport geochemical model was created both for the Finnish and Portuguese sites in the ITERAMS project, by considering different hydrogeochemical units, such as tailing, permeability, mineralogical composition, and pore water chemical composition (Figure 27).

To provide a more comprehensive view on the sustainability of mining processes and products, a new approach was proposed to analyse the social impacts of introducing novel technologies into mining operations in ITERAMS and beyond. It is based on the combination of (1) impacts derived from mining activities on selected stakeholders, and (2) the local communities' perception of the impacts. It was analysed if the technical impacts of the technology could affect the perception of the local population, and therefore the acceptance of the mine. Further, several issues that are not tackled by the technology could be identified. Then several recommendations could be suggested to the company to improve even more the acceptance. This topic is addressed in Chapter 6.2.

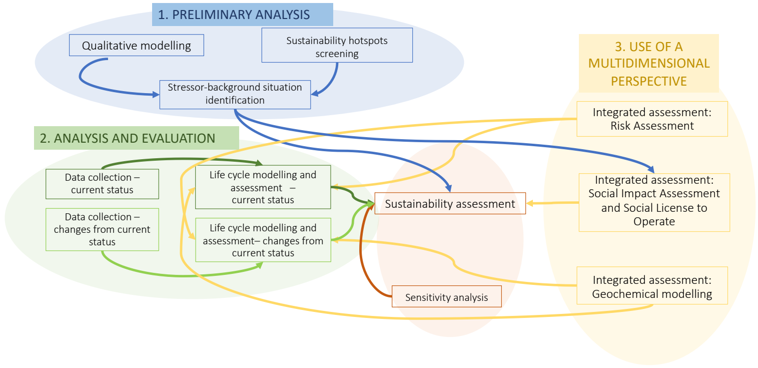


Figure 25. The different steps foreseen by the procedure for the sustainability assessment

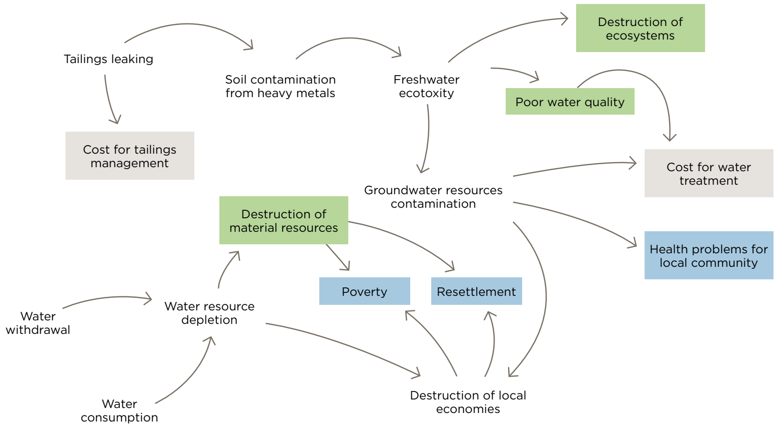


Figure 26. Excerpt of qualitative causal loop model for MINE OPERATIONS (effects on the environmental, social and economic dimensions are highlighted in green, orange and yellow respectively)

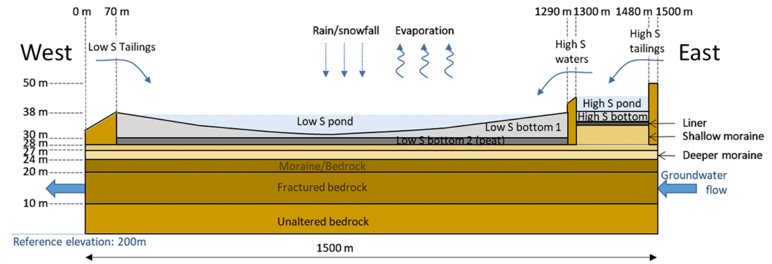


Figure 27. Cross-section of the modelled system for the Finnish mine highlighting the different hydrogeochemical units and the various types of fluxes

4 TWO AND A HALF CASE STUDIES AT MINE SITES

Two ITERAMS researchers while collecting samples at the Kevitsa mine

TWO AND A HALF CASE STUDIES AT MINE SITES

This chapter reports on the sustainability assessment of the ITERAMS novel technologies applied to the sites under study, with a focus on environmental and economic aspects for Kevitsa and Site B. Social aspects are addressed in chapter 6.2. General sustainability considerations are derived for the South African site (Site C), for which specific evaluations could not be made due to lack of data.

It should be noted that the results presented in this chapter are to be interpreted in the context of the mines under study and should not be taken as a general conclusion about the sustainability of the ITERAMS technological portfolio.

APPROACH FOR THE SUSTAINABILITY ASSESSMENT

The sustainability assessment for the ITERAMS technologies in Kevitsa and Site B follows the methodology presented in Chapter 3. A comparative LCA study was performed to evaluate the environmental impacts of mining activities in Kevitsa and Site B before and after the implementation of the novel mining technologies. Primary data were collected for both mines regarding the operation, novel water treatment technologies (DAF and IER), sensors and geopolymers. The life cycle models for the two mines were complemented with secondary data from the ecoinvent APOS 3.6 database to describe the supply chains. Different scenarios were created for the implementation of the ITERAMS solutions at the two sites: a first scenario with the novel water treatment technologies and sensors applied to Kevitsa and Site B; a second scenario with novel treatment technologies, sensors and geopolymers to cover the waste rock dump at Kevitsa and for backfilling at Site B; a third scenario with geopolymers only to cover the waste rock dump in Kevitsa and for backfilling at Site B; a fourth scenario for Kevitsa with novel treatment technologies, sensors and geopolymers to cover the waste rock dump and the tailings ponds. Results are calculated using the Environmental Footprint (EF) v.2, USEtox 2 and AWARE impact assessment methods. Furthermore, a risk assessment is performed to understand the implications of ITERAMS for environmental risk management at mine sites.

A comparative Life Cycle Costing was conducted based on the same models and scenarios applied for environmental LCA. Costs and value added were analyzed for both studied mines and compared before and after the implementation of the ITERAMS technologies. Due to the high confidentiality of economic data, minimal information could be collected as primary data. Most cost data were obtained from secondary sources (literature, ecoinvent database, expert judgement).

Results of the comparative assessment are presented for 1 ton of Copper equivalent[1] in concentrate, which was selected as a common measure to assess the sustainability performance of each site.

SUSTAINABILITY ASSESSMENT OF THE ITERAMS TECHNOLOGIES APPLIED TO KEVITSA MINE

The ITERAMS portfolio for the Kevitsa mine consists of DAF and IER technologies to treat process water before this is recycled back to the processing plant. Calcium and sulphate ion and thiosulphate sensors can be also added to monitor water quality on-site and optimize reagent dosage and water treatment (WT) effort. From a technical point of view, this implies an improvement of flotation performance in terms of chemical usage for processing (−5 %) and recovery rate for copper and nickel concentrates (Cu up to 1.2 % units, Ni up to 1.09 % units); on the other hand, Cu concentrate grade is expected to decrease by 0.60 % units, while Ni concentrate grade could increase by 0.16 % units. Overall, the decrease in Cu grade negatively affects the Cu equivalent which results lower than in the current situation. The recycling rate at Kevitsa is already very efficient (around 90 %), therefore no changes are assumed regarding raw water intake and discharge in the scenario with WT technologies and sensors; indeed, to have an even higher recycling rate, new water treatment technologies would be needed, besides what is foreseen by ITERAMS. On the other hand, when geopolymers are introduced, less water can be discharged (−23 % for scenario 3): a lower volume of tailings can be sent to ponds as they are used for geopolymer creation.

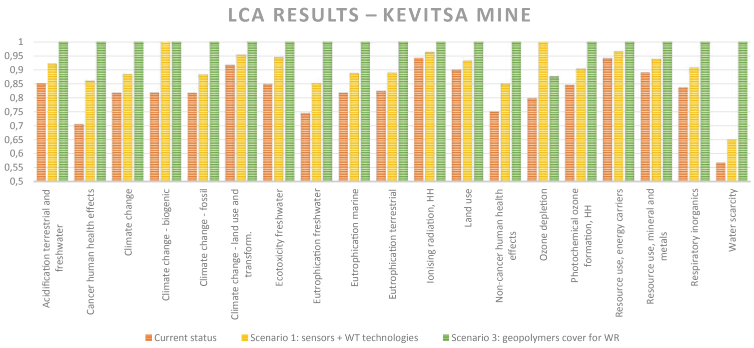


Figure 28. Comparison of environmental impacts at Kevitsa mine among different scenarios with ITERAMS technologies: current status; scenario 1: sensors + water treatment (WT) technologies; scenario 3: geopolymers as cover for waste rock (WR) dump. EF method v.2, results for 1 t Cu eq.

Treating the large volume of process water with DAF and IER at Kevitsa does not appear overall environmentally beneficial, given that the technical performance of flotation does not significantly improve. As shown in Figure 28, scenario 1 (sensors + WT technologies) displays higher environmental impacts in the different impact categories if compared to the current situation without ITERAMS solutions. Specifically, introducing IER technology has an important contribution to impacts. Within IER, ettringite precipitation of resin regenerating solution is the most contributing process, due to Aluminium use and HCl solution for pH regulation. Aluminium and HCl solution are specifically impacting the categories “cancer human health effects”, “non-can-

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[1] Copper equivalent (Cu eq.) is defined as CuEq.% = Cu% + (Σ_i R_i V_i G_i) / ($V_{Cu}R_{Cu}$), where R is the metallurgical metal recovery rate, V is the metal price and G is the metal grade in percent of concentrate

cer human health effects", "ecotoxicity freshwater" and "eutrophication freshwater". In addition, electricity usage for DAF functioning negatively affects the environmental performance of the ITERAMS portfolio. The "water scarcity" category is affected by the water needed for chemical solutions and increased electricity consumption for water treatment, given that the Finnish electricity mix includes hydropower. Introducing sensors on site does not significantly increase environmental impacts, except for "ozone depletion" due to polymers needed for sensor manufacturing. A decrease of Cu equivalent in scenario 1 contributes to larger impacts for "climate change" and "acidification" in comparison to the current status.

Suppose geopolymers are considered as a cover for the waste rock dump at Kevitsa (scenario 3), the environmental performance of mining operations is worse than the current status. This is due to the additional electricity for geopolymer creation and especially to meet the waterglass content of geopolymers (specifically affecting "climate change", toxicity and eutrophication categories). However, it should be noted that applying a geopolymer cover to tailings ponds (scenario 4) can have significant environmental benefits, thus reducing direct impacts on freshwater ecotoxicity (–50 %) and human toxicity, cancer and non-cancer (–24 %), see Figure 29. If the whole life cycle (hence also supply chains) is considered, energy for tailing dewatering for dry disposal and geopolymer creation and chemicals for geopolymers still have a large contribution to impacts, thus overshadowing direct benefits of preventing tailing emissions to groundwater.

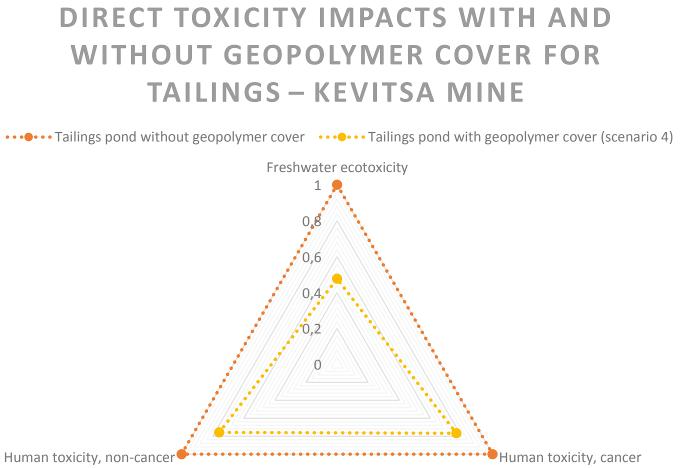


Figure 29. Comparison of direct toxicity impacts at Kevitsa mine for tailings management without (current status) and with geopolymer cover. USEtox 2 method, results for 1 t Cu eq.

In terms of environmental risk management, a lower risk of Acid Mine Drainage thanks to a geopolymer cover for high sulfur waste rocks and tailings would be the main benefit. Furthermore, a geopolymer layer would also decrease the risk of heavy metal leakage into surface and groundwaters and sensors would monitor the quality of water flows on-site, hence helping to comply with environmental regulations.

SUSTAINABILITY ASSESSMENT OF THE ITERAMS TECHNOLOGIES APPLIED TO SITE B

Introducing water treatment technologies and sensors to Site B can result in a lower chemical dosage for flotation (–5 %) and in an improved recovery rate (up to 5 % for the different concentrates). DAF is applied to raw water for the plant, while DAF and IER are applied to Site B to treat process water for the plant. This consists of a much lower volume of water to be treated in comparison to Kevitsa. Therefore, introducing WT technologies and sensors on site (scenario 1) does not result in a much worse (but also not much better) environmental performance in comparison to the current situation (Figure 30). For this scenario, impacts of novel technologies are almost completely balanced by the benefits introduced by them. Furthermore, scaling in pipes was highlighted as a major issue on-site; this can be reduced with ITERAMS if process water quality improves, thus decreasing the formation of calcium sulfate.

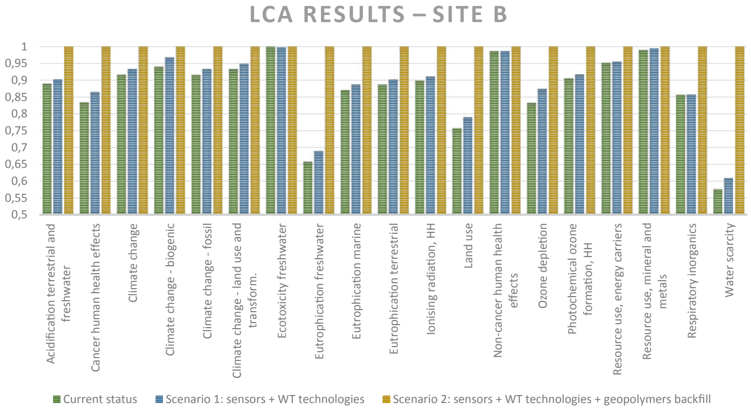


Figure 30. Comparison of environmental impacts at Site B among different scenarios with ITERAMS technologies: current status; scenario 1: sensors + water treatment (WT) technologies; scenario 2: sensors + water treatment (WT) technologies + geopolymers as backfill. EF method v.2, results for 1 t Cu eq.

If traditional backfill with cement binder is substituted with geopolymer backfill and WT technologies and sensors are added on site (scenario 2), the ITERAMS portfolio shows worse performance than the current situation. This impact worsening in comparison to the previous scenario 1 is due to the geopolymer backfill. Indeed, the creation of this material requires chemicals that negatively affect the environmental performance of the mine. Specifically, water-glass and sodium hydroxide contribute significantly to "climate change" and "eutrophication of freshwater". Water-glass alone has a large impact on human health (cancer effects), ozone depletion and land use – due to the construction of factories for chemical production. The water scarcity category is negatively affected by water needed for chemical production, chemical solution preparation and the increased electricity for WT technologies, considering that the Portuguese electricity mix also contains a share of hydropower.

Water recycling at Site B is very high, up to 94 %, therefore the novel water technologies will not influence raw water intake and discharge. However, the presence of sensors can improve water quality monitoring and ensure that if there is any leakage, the water quality will improve. This will also reduce the risk of polluting water resources important for the livelihood of local communities and acceptance of mining operations (see Chapter 6.2).

From an economic perspective, producing geopolymer backfill will have higher cost than the traditional cement backfill (Figure 31). Main cost contributors to geopolymer backfill are the chemicals needed for the material creation, namely water-glass, sodium hydroxide and plastifier. Geopolymers used for waste rock and tailing cover at Kevitsa mine are up to 35 % cheaper than geopolymer backfill. Also, in that case, reagents contribute the most to economic impacts.

If the value added (the difference between revenues and expenses) is considered for mining operations at Site B with and without the ITERAMS technologies, all the three ITERAMS scenarios show an improvement in terms of the value generated in the whole life cycle, especially if geopolymers are introduced (Table 1). Indeed, introducing the novel technologies increases direct mining operating costs only up to 3 %, while generating in turn a concentrate with higher copper equivalent, and hence more value. A positive economic impact can be highlighted for both mines in terms of value generation in the life cycle if the ITERAMS portfolio is implemented on-site.

Kevitsa	**Current status**	**Scenario 1: sensors + WTT**	**Scenario 2: sensors + WWT + geopolymers for WRD**	**Scenario 3: geopolymers for WRD**	**Scenario 4: sensors + WWT + geopolymers for WRD and tailings ponds**
EUR/t Cu eq.	7616.96	+4 %	+19 %	+14 %	+39 %

Site B	**Current status**	**Scenario 1: sensors + WTT**	**Scenario 2: sensors + WWT + geopolymer backfill**	**Scenario 3: geopolymer backfill**
EUR/t Cu eq.	7141.02	+2 %	+31 %	+29 %

Table 1: Value added calculation in the life cycle for Kevitsa and Site B before and after the implementation of the ITERAMS technologies (change in comparison to current status)

SUSTAINABILITY CONSIDERATIONS OF THE ITERAMS TECHNOLOGIES APPLIED TO PT MINE A

In the case of the Site C in South Africa, the implementation of a geopolymer cover for tailing ponds can prevent dust formation and the spreading of tailing dust by the wind. This can have a direct positive effect on toxicity categories, such as freshwater and human toxicity, especially if it is considered that some villages are located close to the mine. However, as the two other validation cases already demonstrated, it is important to pay attention to possible trade-offs, such as higher environmental impacts for those categories affected by reagents and electricity for geopolymer production.

From the point of view of water quality, if the issue of bacterial growth in process water is successfully addressed, this may increase water recycling possibilities with important benefits from an environmental and economic point of view for a water-scarce area. Not less, positive social impacts can be achieved if the recycling rate can increase and less tailings area is needed because a share of tailings can be used to create geopolymers. This way, land use can be reduced thus preventing relocation of communities close to the mine and less water resources needed for agriculture in the area may be consumed for mining.

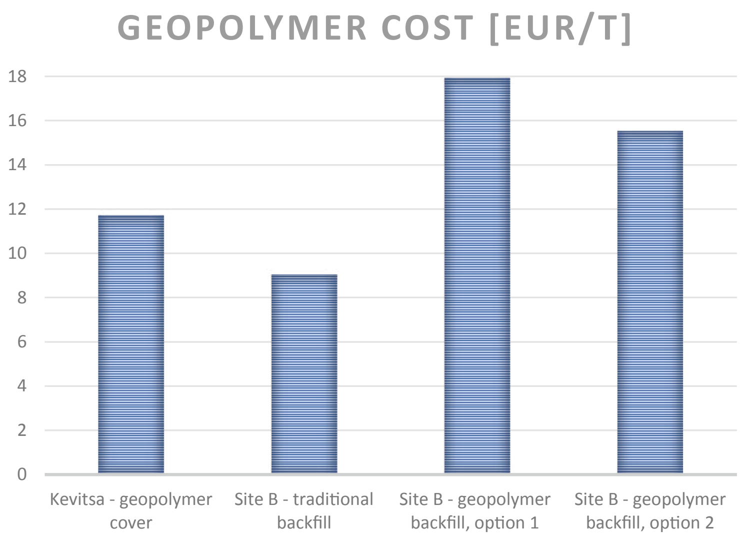


Figure 31. Comparison of cost between geopolymer cover for Kevitsa mine and traditional and geopolymer backfill for Site B

5 IS THE ITERAMS PORTFOLIO OF TECHNOLOGIES REALLY SUSTAINABLE?

Erzberg open-pit mine near Loeben, Austria, which was visited by the ITERAMS team

IS THE ITERAMS PORTFOLIO OF TECHNOLOGIES REALLY SUSTAINABLE?

The ITERAMS project developed, over more than three years of work, a portfolio of different technologies to tackle various problems in mining, from process water quality to water and waste management. Within each technology developed it is possible to find a wide range of alternatives, such as different chemical dosages and combinations. Furthermore, depending on the mine, only some of or all the ITERAMS technologies may be needed. The ITERAMS portfolio was created with the idea that each mine site is different and hence requires site-specific solutions, rather than a one-size-fits-all approach.

The technological complexity and variety of the ITERAMS portfolio have an influence on the sustainability assessment of the technologies, meaning that it is hard to evaluate the sustainability of the ITERAMS project in general. It is indeed meaningful for different stakeholders (mining companies, LCA practitioners, NGOs, local communities…) to consider the sustainability of the technologies specifically for each site. Nevertheless, testing the ITERAMS portfolio in the three validation sites offered important insights on positive and negative sustainability impacts and risks of the technologies for very different contexts. This was useful to highlight hotspots, trade-offs, and areas of further work for ITERAMS technological development in future research.

For how it was conceived, the ITERAMS project offers different and combinable pathways for more sustainable mining. To which extent and how this can be achieved needs to be considered for each mine, by paying attention that trade-offs or impacts in the life cycle do not overshadow direct benefits. It should also be noted that if monitoring measures are already in place on-site and if the mine is already putting effort into improving the environmental performance, benefits achievable with ITERAMS may not be significant.

At the beginning of the project, a sustainability hotspot screening was performed to identify main hotspots in mining and to investigate whether ITERAMS could address widely recognized sustainability issues in the sector. Tailings management and energy use for ore processing emerged as hotspots from an environmental and economic point of view. Toxic emissions from tailings ponds are a major issue for aquatic ecosystems and human health, thus highlighting also potential implications for local communities. From a social point of view, employment, fair salary for workers and dependence of communities on water resources could be identified as the main hotspots. It can be concluded that most of the identified sustainability hotspots are tackled by ITERAMS.

For each of the main technology groups developed by ITERAMS, it appears important to discuss on the one hand potential positive sustainability implications and on the other hand trade-offs and hotspots that may arise when implemented on site, based on the experience of the three validation sites.

WATER TREATMENT TECHNOLOGIES AND SENSORS

Water treatment technologies were developed in ITERAMS to enhance water quality at different points at the mine sites so that the overall quality of water recycled to the processing plant could improve. This would enable mines to increase the recycling rate, decrease raw water intake and water discharge. This may have important benefits for water-scarce areas where mines are often a competing user of water resources with local communities that need water for agriculture and farming. In general, discharging less water to local rivers and lakes can also contribute preserving natural resources and landscape, especially when they are important destinations for tourism or have a local cultural value. Furthermore, a better quality of recycled process water can improve flotation performance, thus reducing chemical consumption and improving concentrate value. In that case, valuable metals and minerals can be produced with less effort in terms of chemicals, energy, water and waste. If this is achieved, it will benefit all environmental impact categories, especially climate change, human toxicity and water scarcity.

The application of ITERAMS water treatment technologies at the validation sites has shown that economic benefits can be achieved in terms of a higher value-added generated in the life cycle, especially when coupled with geopolymers. However, from an environmental point of view, different considerations can be drawn, and there is room for improvement. The amount of water to be treated with the technologies and the initial water quality have a big influence on environmental impacts, as more water for treatment and low water quality mean more reagents and energy. Specifically, resin regeneration in IE emerged as an environmental hotspot, especially regarding ettringite precipitation of the NaOH regenerating solution. Ettringite precipitation accounts for most impacts for treatment with IE, see Figure 32, due to aluminium and chemical usage. The choice of the chemical solution for pH regulation before ettringite precipitation appears crucial for environmental effects, considering for instance that HNO_3 has larger impacts than HCl. As for DAF, reagent dosage emerged again as an essential parameter for environmental impacts, especially regarding the coagulant choice where PIX (ferric sulfate) was found to perform environmentally better than PAX (polyaluminium chloride).

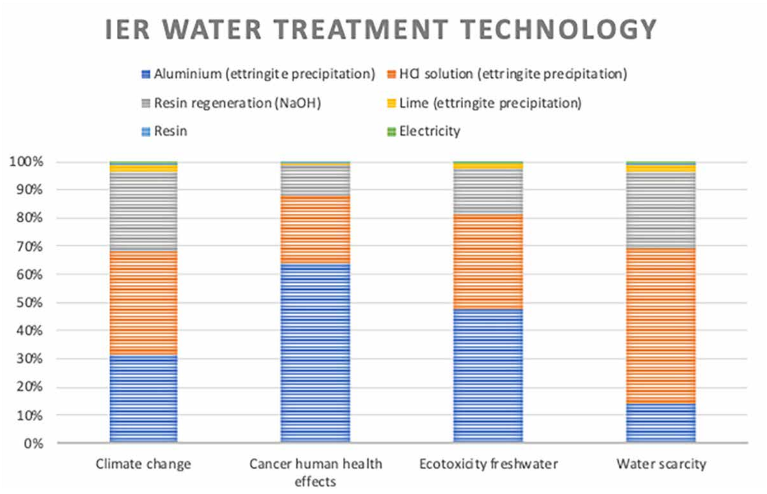


Figure 32. Contribution analysis for IER water treatment technology in Kevitsa for selected impact categories, EF method v.2. Results for 1 m^3 of water treated

Sensors play a crucial role in achieving suitable process values for water quality. Environmental benefits achievable with the introduction of sensors on-site are significant in comparison to very low environmental effects of sensor manufacturing and operation (a small amount of electricity is needed for functioning) and very low cost (10–20 EUR per sensor).

GEOPOLYMERS

Implementing a geopolymer layer to cover tailings and high sulphur waste rocks, has important direct benefits for toxicity impacts on humans and freshwater. Beside reducing short- and long-term impacts of tailings emissions, installing a geopolymer cover can significantly improve environmental risk management for mining companies. Environmental risks often trigger other risks directly or indirectly (Figure 33). Therefore, by reducing AMD risks with a geopolymer cover, contamination of soil, groundwater reserves and other water bodies can be prevented. Furthermore, implementing a dry tailings disposal would reduce the risk of environmental accidents, such as dam failure, and land consumption. Pollution of water resources and resettlement are two environmental consequences that are directly observable by local communities: protection of water resources and land has social and socio-economic consequences and contribute to creating a relationship of trust between mining companies and local communities [13]. However, it should be noted that geopolymer production requires chemicals and energy for mixing and tailings dewatering, which emerged as environmental hotspots from the LCA performed for Kevitsa and Site B. In this latter case of the Portuguese mine where geopolymers were used as an alternative material to cement backfill, trade-offs of using more chemicals – in particular waterglass – could be highlighted.

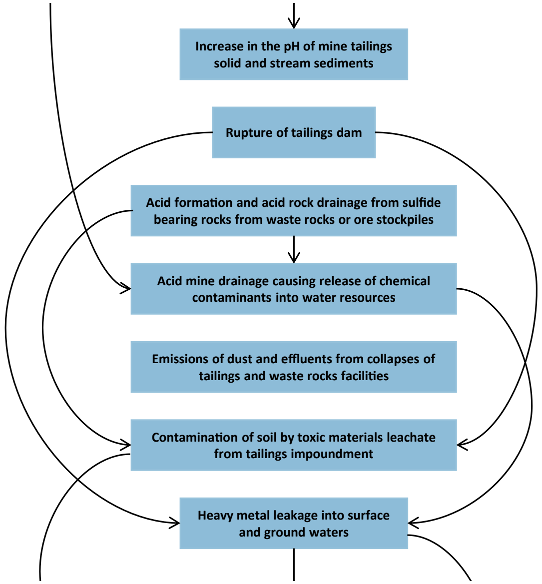


Figure 33. Cause-effect relation among environmental risks at mine sites

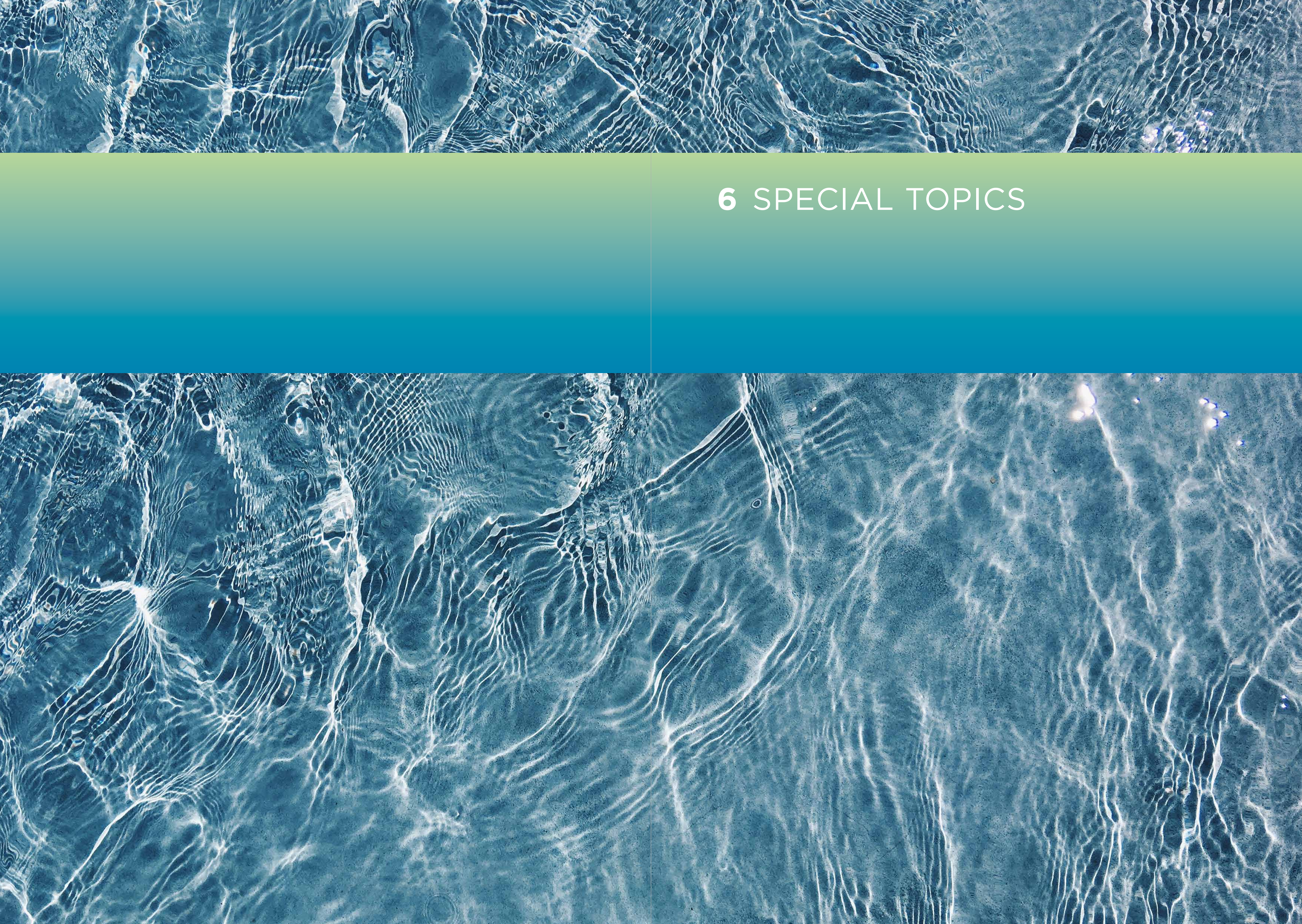
If geopolymers are introduced on site, overall direct mining operation costs increase by 7 % in the case of geopolymer cover for waste rocks at Kevitsa and by 3 % in the event of geopolymer backfill at Site B. In the scenario of a dry tailings disposal and geopolymer cover for Kevitsa, costs would increase by 20 % in comparison to the current situation. However, the value-added achievable with the combination of geopolymers and WT technologies would still be positive if the whole life cycle is considered.

ORE SORTING

Ore sorting in ITERAMS has shown a high potential from a technical point of view: less low-grade material would be processed, concentrate value would increase, tailings to be disposed would be reduced. Given that, all consumables, energy and water use for ore processing can be potentially decreased, with important economic and environmental benefits. However, it should be noted that waste rocks would increase together with the related management effort and eventually AMD generation. Moreover, ore sorting would require the installation of novel technologies which need energy for functioning.

Experiments were conducted on ore sorting for Kevitsa mine, showing promising results. However, further reasoning about changes in consumables, energy and water use in the plant was not part of the project, therefore ore sorting technologies were not included in the sustainability assessment of the case studies. Combining ore sorting with the other ITERAMS technologies could have relevant sustainability implications that should always be considered in the specific context of the site under study.

6 SPECIAL TOPICS



SPECIAL TOPICS

The previous chapters have primarily focused on the technical solutions and their effects on sustainability at the given mine sites. In addition, ITERAMS has produced two conceptual results, from different areas, but both important for the sustainable construction and operation of mines. The first outcome resulted from the validation work of the water treatment technologies and provides a protocol for mine sites for managing closed-loop water cycles. The second outcome describes a methodology which can be applied by mines, and their stakeholders, for measuring the influence of a technology's implementation on the social acceptance of mines.

6.1 A PROTOCOL FOR MANAGING CLOSED WATER LOOPS AT MINES

Closing water loops at mines is new territory and poses practical challenges to the operational management at a plant. An important objective of ITERAMS was, therefore, to not only investigate the behaviour of water in closed loops and the performance of various water treatment methods but to give guidelines for the systematic evaluation of water management systems around mine sites, with a special focus on the effects of water quality on process performance. This was achieved by the development of a standardized protocol for smarter water recycling and management.

The main objective is to anticipate and prevent the adverse effect of closing the water circuit on the process performance nd maintenance. The protocol is built based on a series of questions that minerals processing engineers should answer before embarking on any major modification in the water circuit, complemented by a selection of (newly developed) tools that could support the plant management.

This systematic approach will bring benefits both in the design phase of new plants and for evaluating different alternatives for closing water circuits and efficient water management in already existing plants.

THE FINAL PROTOCOL IS A COMBINATION OF 7 SUB-PROTOCOLS:

1. Sub-protocol for evaluating water quality in relation to plant performance
2. Sub-protocol for identifying adverse components and their limit
3. Sub-protocol for evaluating the effect of bacteria
4. Sub-protocol for predicting the variation of water quality and its impact on flotation
5. Sub-protocol for implementing water treatment solution
6. Sub-protocol for monitoring and controlling water quality
7. Sub-protocol for implementing water management in plant design

Sub-protocol 1 describes methodologies for evaluating water quality for plant performance investigation purposes and not for environmental purposes. Due to the difference in properties of mine discharge water and mine process water, methodologies that can be applied for mine discharge water (for environmental monitoring) might not be applicable for mine process water (for process performance improvement). This protocol points out the limits and disadvantages of the current practices for evaluating mining process water and provides suggestions for improvements. Precisely, this protocol contains guidelines for (1) analyzing historical data to generate hypotheses about the potential impact of water quality on the plant performance, (2) sampling mine process water, (3) stabilizing and analyzing mine process water, and (4) building the water balance which is needed for the elemental balance in the flotation circuit.

Sub-protocol 2 gives guidelines on on-site and laboratory work to be completed to determine the components of the process water which may be harmful to the flotation process. This protocol contains novel and innovative laboratory and industrial approaches both to study and evaluate dynamic systems observed in the flotation circuit. This protocol aims to provide tools (1) to determine the possible effects of different inorganic and organic species on the solid-liquid and air-liquid interfaces and thus the efficiency of flotation, (2) to measure with simple diagnostic tools, and (3) to determine the limit that adverse components can affect the flotation circuit

Sub-protocol 3 provides guidelines for studying the microbial load within the flotation circuit and its effect on the flotation performance. Innovative methods for preserving and analyzing microbial samples in systems containing solids have been developed and integrated into the protocol. Additionally, the effect of microbiology on the three phases interactions could be investigated with novel laboratory diagnostic tools.

Sub-protocol 4 describes the dissolution loop protocol that allows the prediction of changes in process water quality in the case of close water recirculation. The dissolution protocol can predict the variation of the water quality over time due to the dissolution of the ore when the plant is operated in a closed water circuit. Therefore, this protocol should be used as a tool to complement the traditional processing plant design and water treatment facility selection and dimensioning. Additionally, the protocol allows the testing of the flotation sensitivity of the ore with the water matrix that has been created in the dissolution loop. The tests will help to predict in which direction the performance will incline if the water is recycled. In the case that negative impacts on the flotation or the maintenance are observed, it could be anticipated beforehand and the solution could be already included in the plant design or prevented by an appropriate water treatment process selection.

Sub-protocol 5 summarises technologies for water treatment that have been developed within the frame of the project. Those technologies target different adverse components that have been identified such as fine suspended solids, thiosalts, sulfate, and calcium. The methodology was firstly developed in the laboratory scale and later validated in the mine-site. On-site flotation tests performed with treated and no treated water could confirm the applicability of the methods for treating water and improving process performance.

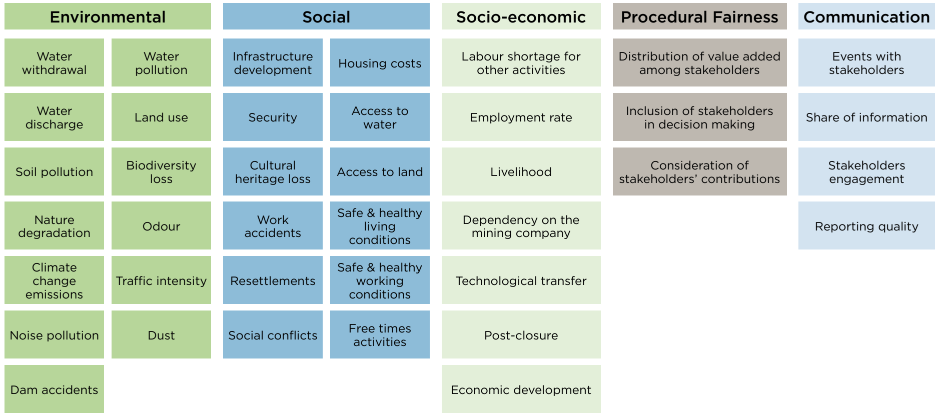
Sub-protocol 6 provides novel tools for monitoring water quality, such as sensors and on-site analysis. Additionally, this protocol highlights the need to apply multivariate statistical methods to control the water quality which is characterized by a complex water matrix. A key advantage of multivariate statistics over univariate statistics is that all available data is used together for monitoring and diagnostic purposes. These approaches treat all data simultaneously, therefore, they take into consideration the relation of the variables to each other. This aspect is essential for reducing the monitoring charts.

Sub-protocol 7 mentions the importance of taking into consideration the effect of water recycling in the plant design. Knowing the potential impact of recycling water in plant performance and plant maintenance will allow the design engineer to choose a more suitable ore treatment process and anticipate room for process modification and improvement. Additionally, implementation of the water treatment method in the early phase of plant design could help to reduce cost due to plant modification, maintenance, and decline of performance in later modifications.

6.2 UNDERSTANDING AND MANAGING A MINE'S SOCIAL LICENSE TO OPERATE

Mining activities alter the milieu of mining communities either originating a direct social impact – employment rate – or through the influence of environmental impacts on social aspects – resettlement due to water pollution. Historically it has been claimed that mining companies fail to listen and consider the needs and requirements expressed by local communities. This can lead to conflicts between mining companies and communities, which represents a big hurdle for mining companies and can be a disadvantage for the affected stakeholders. Hence, the acceptance of a mining site among local communities enhances the sustainability of the operation and it is crucial to ensure that the interests, needs, and livelihood of local stakeholders are considered. The Social License to Operate (SLO) has emerged during the 1990s as a somewhat catchy, easy to communicate term to summarise the stakeholders' acceptance of mining activities [14].

The most common impacts derived from mining activities that simultaneously affect the SLO were collected and presented in Figure 34. Five pillars were identified: environmental, social, socio-economic, procedural fairness, and communication. Although the first three pillars could appear as sufficient to define the social impacts from mining, procedural fairness towards the stakeholders and good quality of communication are key for gaining social acceptance. A wide range of perspectives on the same issue from different stakeholders is expected. It is important to pursue the inclusion of all of them. A basis collection of stakeholders is displayed in Figure 35.



Environmental		Social		Socio-economic	Procedural Fairness	Communication
Water withdrawal	Water pollution	Infrastructure development	Housing costs	Labour shortage for other activities	Distribution of value added among stakeholders	Events with stakeholders
Water discharge	Land use	Security	Access to water	Employment rate	Inclusion of stakeholders in decision making	Share of information
Soil pollution	Biodiversity loss	Cultural heritage loss	Access to land	Livelihood	Consideration of stakeholders' contributions	Stakeholders engagement
Nature degradation	Odour	Work accidents	Safe & healthy living conditions	Dependency on the mining company		Reporting quality
Climate change emissions	Traffic intensity	Resettlements	Safe & healthy working conditions	Technological transfer		
Noise pollution	Dust	Social conflicts	Free times activities	Post-closure		
Dam accidents				Economic development		

Figure 34. Most common impacts from mining activities influencing SLO

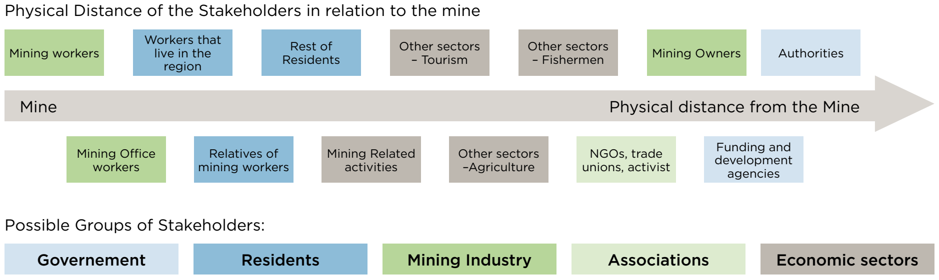


Figure 35. Potential stakeholder groups of mining activities

An innovative approach to determine the social impacts from mining activities was developed for ITERAMS and beyond combining the impacts on the stakeholders and the communities' perception; the first are named technical impacts and the second perceived impacts. The new approach was tested for s applying online available information, and the results of online interviews. Additionally, fieldwork was carried out in South Spain to analyse the data collection process in detail. The developed methodology is displayed in Figure 36. The 13 steps are explained with an example of its application for Site B for the social Aspect dependence of local communities on water resources.

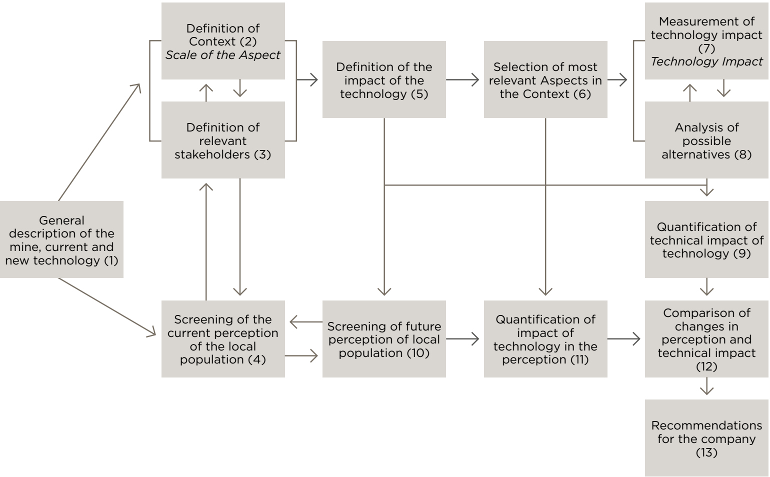


Figure 36. 13-step methodology for the social assessment of mining activities

1. An objective description of the mine describing the current and the new technologies to be implemented
2. Five Contexts, each of them containing several Aspects, are explored based on objective information. These are the vulnerability of local communities analysing aspects like dependence on water resources or health status of the population; the risks in the mining sector related to a safe operation; conflict with other economic sectors like agricultural activities; the local resources including aspects water quality or biodiversity; the national and local risks apart from mining like the level of pollution; the share of the sector in national GPD and local economy; and the communication and procedural fairness. The importance of every Aspect is quantified with a predetermined scale, which is presented in table 1 as an example of the Aspect *dependence of local communities on water resources.* The higher the Scale of Aspect, the more important is the Aspect.

Alternatives	Identification procedure	Scale
High dependence	Water resources important for local communities (water level reservoir in las year < average), the main consumption of water from the reservoir is the mine	1.00
Medium dependence	Water resources important for local communities (water level reservoir in las year < average), the main consumption of water from the reservoir is another activity	0.66
Low dependence	Water resources not important for local communities (water level reservoir in last year > average)	0.33

Table 2. Scale of Aspect definition

The Aspect *dependence of local communities on water resources* for Site B was evaluated as "Medium dependence" with a Scale of Aspect of 0.66. The decision was made based on the status of the Santa Clara Reservoir [15] from where the mine takes water since 1991 [16], and of the Reservoir Monte da Rocha, which is used by the local population [17]. Besides that, the Oeiras River, which receives water from the mine, should be preserved, since the river is the habitat of endangered species and also due to the presence of fishing activities in the region [18].

3. Stakeholders are selected in an iterative process between (2), (3), and (4).
   Authorities, environmental agency, trade unions, residents, farmers, mining workers.
4. Each relevant Aspect identified in (2) for the selected stakeholders in (3) is evaluated regarding the local communities' perception – they can be identified as "Good", "Indifferent", or "Not Good".
   Dependence of local communities on water resources It is considered as "Not Good" for the local population according to posted information in social media and comments in local newspapers/ according to interviews carried out with local stakeholders.
5. All Aspects defined in (2) are qualitatively analysed in terms of whether they may be affected by the technology (ITERAMS) or not. Additionally, it is identified if the technology would only affect certain conditions.
   Potential improvements from ITERAMS are identified.
6. The outcomes of (2) and (5) are jointly considered to decide which Aspects are the most relevant. If the importance of an Aspect is higher than zero, and it may be potentially affected by ITERAMS, it is considered for further evaluation.
   According to the results for (2) and (5), the *dependence of local communities on water resources* is considered as a relevant Aspect.
7. The scale presented in table 2 is applied to quantify the impact of the technology on different aspects for different stakeholders.

Classification	Description
−1	Implementation of the technology will have a negative impact in this Aspect, in this term, for this Stakeholder
0	Implementation of the technology will not affect this Aspect, in this term, for this Stakeholder
+1	Implementation of the technology will have a positive impact in this Aspect, in this term, for this Stakeholder

Table 3. Definition of the Technology Impact

Classification	Description
−1	Implementation of the technology will have a negative impact in this Aspect, in this term, for this Stakeholder
0	Implementation of the technology will not affect this Aspect, in this term, for this Stakeholder
+1	Implementation of the technology will have a positive impact in this Aspect, in this term, for this Stakeholder

Table 4. Definition of the Technology Impact for Aspect dependence of local communities on water resources at Site B

8 The conditions defined in (5) support the building of scenarios that may originate from different outcomes.
It does not apply to Site B.

9 Scores are calculated to quantify the impact of the technology for every stakeholder group; the Scale of the Aspect (1) is multiplied by the technology impact (7). The obtained result indicates the relevancy of an Aspect from a minimum of −1 to a maximum of +1. It is possible to aggregate the scores for a Context, a stakeholder group, or even to a single score evaluating the general impact of ITERAMS.
For most of the stakeholders, the results of multiplying the Scale of the Aspect (0.66) and the Technology Impact (+1) is 0.66.

10 Combining the Current Perception (4) and the Technology Impact (7) the future perception. An 8-level scale indicates how the perception will be affected by the technology, from negatively affected to positively affected.
Residents, other economic activities, and associations like NGOs, activists, and trade unions will likely perceive that the situation with access to water, which is currently an issue, will be improved. On the other hand, mining (and related activities) workers will experiment a lower perception.

11 The Future Perception (10) is multiplied by the Scale of the Aspect (2) to quantify the impact of the technology on different Aspects and Stakeholders. The obtained result indicates the relevancy of an Aspect from a minimum of −1 to a maximum of +1.
The obtained score for Residents, other economic activities, and associations is 0.66 (higher perception), while the score for mining (and related activities) workers will not be affected is −0.33 (lower perception).

12 A joint analysis of (9) and (11) supports the understanding of how the impacts of the technology can affect the Social License to Operate.
It becomes clear that different stakeholders perceive the impacts differently depending on their connection to the mine.

13 The identification of the social impacts and how they are perceived from the communities in the present as well as in the future, after incorporating new technologies, provides mining companies with valuable information; whether the investments will result in an improvement of the Social License to Operate or not.
Water availability and water quality issues can be improved with the technologies. This information should arrive at the local communities to affect social acceptance. Further, it needs to be communicated in a way that people understand how it affects their daily lives. The perception of environmental agencies controlling water issues will be positively affected.

DATA COLLECTION PROCESS

One of the most challenging points of social assessment is the data collection. The access to valuable information is difficult due to three main reasons: confidentiality issues on the side of the mining company, access to all stakeholders, and winning the trust of the stakeholders. In a first step, data can be collected through content analysis of media content, official documents, statistics, or previous literature. Ideally, this provides a picture of context and of the potential stakeholders in order to start a consultation process, that can be performed online, in the field, or as a combination of both. During the consultation interviews are carried out and in the best case also informal conversations, where stakeholders more relaxed are inclined to talk. A third step for data collection is observation, that can only take place in the field. This includes a visual recognition of the area and the observation of stakeholders' behaviour.

For the assessment of Site B, content analysis and online consultation were followed for data collection. The selected mine for the consultation and observation steps on the field were carried out at mine in South Spain located in the Iberian Pyrite Belt (same as Site B). Prior to the field work, content analysis indicated a high economic dependence on the mine in an area with low salaries and high unemployment rates. Also, water issues were identified according to a sentence against the mine management due to illegal water withdrawal. During consultation different opinions were found even within one stakeholder groups. For example, bigger trade unions on the agricultural sector find the presence of the mine as positive because of the deals that were made with local farmers. Conversely, local trade unions identified the deals as a failure and not sustainable in the long term. Mining workers have also expressed different opinions; from total acceptance, to stating that what happens inside the mine is very negative for the environment. The visual recognition of the river and streams around the mine confirmed the existence of pollution; however, not generally perceived as an issue by the local population. Additionally, tap water is used for drinking purposes and has a good taste. An indication of the unemployment level in the area could be the regular high presence of locals in bars and restaurants through the day. This fact was also confirmed by several residents.

It is clear that field work – combining conversations and observation – can indicate hidden aspects otherwise not visible. These data can improve the data and the quality of the results when applying it in the presented methodology.

7 WHAT DID WE ACHIEVE IN ITERAMS

ITERAMS team while visiting the Erzberg mine
near Loeben, Austria

WHAT DID WE ACHIEVE IN ITERAMS

Towards the end of the ITERAMS project, it is good to step back and check what has been achieved. What are the technical and conceptual results of the ITERAMS project?

For one, ITERAMS brought together about 30 institutes and 250 persons, with collaboration from the mining industry to mining technology providers to science and consultancy, in about 7 countries and 2 continents, and led to a successful exchange of knowledge and experiences.

ITERAMS brings substantial advancements in water treatment technologies, in ore processing, and especially for closing the water cycle in mines. This advancement refers to progress on individual technologies (DAF, ion exchange, filtration, among others) but also in a smart and efficient combinations of the technologies. The different validation mine sites in the project confirmed that there is no "one ITERAMS solution" for closing the water cycle, consisting of a certain pattern of technologies that are interconnected in one approved set, but rather, ITERAMS is offering a solution portfolio, which has been tested and validated in small scale. This solution portfolio should be adapted to the specific requirements of a mine site and its operating mode.

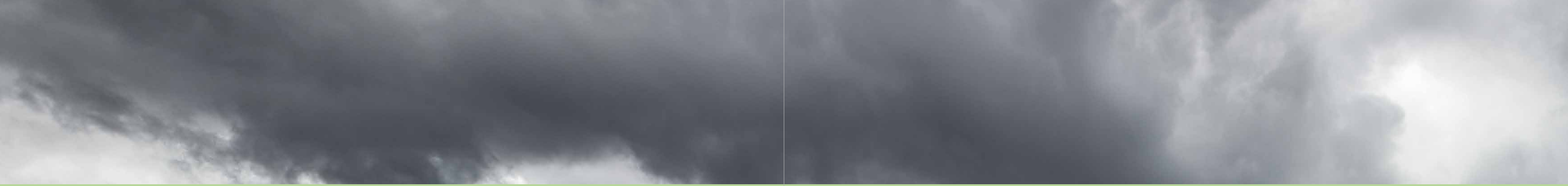
Further, ITERAMS achieved a better understanding of conditions that are suitable for creating geopolymers from tailings obtained from ore processing and was able to successfully create these geopolymers and validate the models and concepts in relevant tests. It was no surprise to see that the initial properties of tailings vary tremendously from mine to mine, and that a "one fits all" approach and recipe for obtaining geopolymers is out of the question. This is further explained and elaborated in chapter 2.

Sensors are an essential element in a well-managed water circulation system; in ITERAMS, new sensors for measuring ion concentration in water streams have developed, based on Ion-Selective Electrodes (ISE). Conceptually, a water treatment protocol has been developed, to guide interested users towards a promising and effective water treatment design, for a mine site.

Not the least, a sustainability assessment for mine sites has been developed and successfully applied, that is at the same time able to capture the various sustainability effects of a mine operation, on-site and to local communities, as well as through the supply chain and life cycle, for environmental, social, and economic impacts. For validation sites with very different conditions, a complete sustainability model has been created. The approach includes a procedure of how to understand and evaluate a social license (SLO) to operate for a mine site, and aspects affecting this SLO. A tiered approach, with an initial qualitative modelling and hot spot screening, helps to identify and focus on those parts of the mine and model that matter, and thus to make the modelling efficient, and also meaningful. Further, the approach reflects a diversity of mining backgrounds, mining operation modes, and can adapt.

ITERAMS project team, meeting in Orléans, France

With ITERAMS' results, it is thus possible to close the water cycle in a mine site, to produce, depending especially on geological conditions, geopolymers from residues of the treatment of the circulated water, to assess the sustainability of the operations, and to guide and steer the operation of the mine towards sustainability.



View on the Erzberg open-pit mine in Austria

8 CONCLUDING, WHAT DO ITERAMS’ PROJECT SOLUTIONS OFFER?

CONCLUDING, WHAT DO ITERAMS' PROJECT SOLUTIONS OFFER?

The ITERAMS portfolio offers different technologies for (1) water treatment, (2) geopolymer creation to be used as cover for waste (tailings and waste rocks) or as backfill material; (3) water quality monitoring through sensors; (4) ore sorting; (5) a methodology for an integrated life cycle sustainability assessment of mining technologies; and (6) a protocol for water management. Therefore, results included both technical experiments and findings as well as environmental, social, and economic sustainability -qualitative and quantitative- evaluations. The above-mentioned methodological developments can also be considered as a core outcome of the ITERAMS project. Given the wide range of technical, sustainability, and methodological results achieved, ITERAMS addresses the needs and issues of different stakeholders related to mining and the raw material sector.

ITERAMS FOR MINING COMPANIES

ITERAMS offers a number of technical solutions to tackle crucial challenges for mines: how to handle and improve water and waste management to be more efficient, hence increasing productivity and decreasing costs, and to comply with local environmental regulations. The developed water management protocol describes step by step different actions to be undertaken to close the water loop and choose the best water treatment technologies. In recent years, we faced the growing demand for social and environmental responsibility of mining operations arising from local communities and society as a whole. Positive sustainability impacts, hotspots, and trade-offs of the ITERAMS portfolio detected with the LCSA represent a useful starting point to orient technical choices towards more a sustainable mining. ITERAMS can influence the social acceptance of the mining activities by improving the environmental, social, and socio-economic effects derived from the operation of a mine. Mining companies may also go beyond to improve the social acceptance by working on issues that are not tackled by the new technologies and by treating the local communities fairly and by establishing a good communication.

ITERAMS FOR LOCAL COMMUNITIES

ITERAMS demonstrated that novel mining technologies can address environmental, social, and socio-economic issues affecting local communities. Environmental risks of mining operations can be reduced, thus preserving health and safety of local populations and natural resources (land, water) important for their livelihood. The main identified social issues related to mining were water issues, employment, and economic development. A positive effect of the novel technologies on the social hotspots is possible. Beyond the technical improvements, to consider the stakeholders' opinions, perceptions and views appears crucial to create a relationship of trust and respect with local communities. The project proposed a methodology to evaluate, either in a qualitative or quantitative way, social impacts, and changes in the SLO if novel technologies are introduced on site. The LCSA framework developed in ITERAMS ensures that considerations on social and environmental responsibility of mining and implications for local communities are part of the evaluating process of novel technologies.

ITERAMS FOR LOCAL GOVERNMENTS AND OTHER INSTITUTIONS

Local authorities worldwide require mining companies to reduce pressure on water resources and to comply with environmental regulations on emissions, water discharge, and quality and waste disposal. ITERAMS offers a portfolio of technologies that address different requirements to be met for environmental regulation compliance. With ITERAMS technologies it could be easier to meet these requirements. Furthermore, if mining companies manage to reduce their environmental footprint by implementing ITERAMS technologies, local authorities may promote more stringent environmental regulations, based on the achievable environmental performance with ITERAMS. This may be more significant for those countries that lack of strict mining environmental legislation and for those sites where water and tailings management is not yet successful. Local governments should also take care that mining companies behave socially responsibly and that no conflicts arise with local communities: by addressing social issues in mining and providing a way to evaluate them, ITERAMS can help to build and preserve good relations between companies and communities and to better handle local resources.

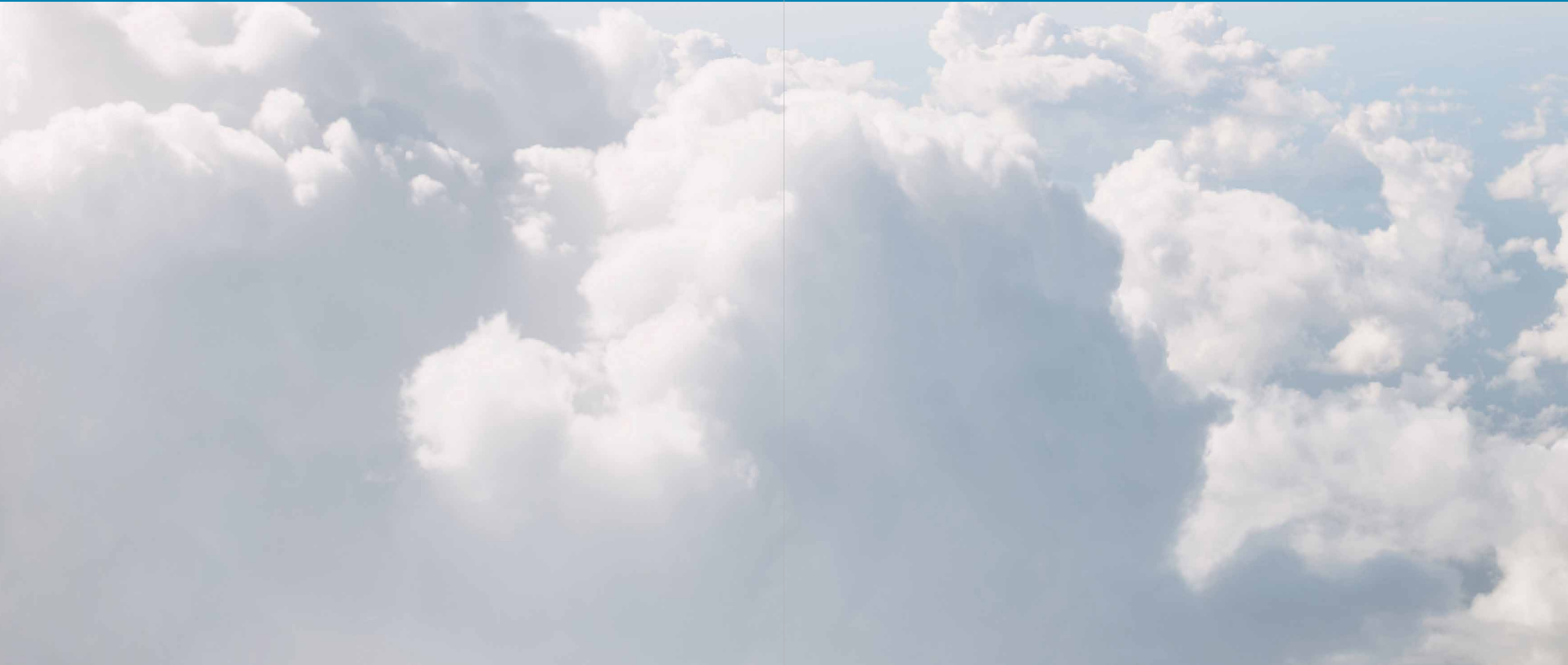
ITERAMS FOR NGOS

NGOs in mining contexts often work on monitoring environmental and social impacts of mining activities and sometimes act as an intermediary between local communities and the mines. The results of the LCSA can offer useful information on positive and negative impacts of the novel ITERAMS technologies on mining operations. Furthermore, ITERAMS offers a methodology for social assessment and for evaluating social perception on mining that can be applied by NGOs in their daily work.

ITERAMS FOR THE SCIENTIFIC COMMUNITY AND SOCIETY IN A BROADER PERSPECTIVE

The scientific community will benefit from the methodological advancements and findings achieved by the ITERAMS project both in terms of sustainability and technologies. ITERAMS can be considered as a starting point to explore areas of further work in future projects, but also for on-going research activities, for instance about LCA, risk assessment, and all the other technological aspects (microbial contamination of process waters, alkali-activated materials ...). Not least, society in a wider perspective can benefit from the achievement of the ITERAMS project, when it goes in the direction of supplying raw materials by consuming less resources and reducing or avoiding impacts.

9 OPPORTUNITIES FOR FUTURE WORK



OPPORTUNITIES FOR FUTURE WORK

ITERAMS was an ambitious project with about 30 partners from all over Europe and even Africa. In 3.5 years, it was possible to make significant advancements and achievements, as indicated in the previous chapters. Yet still, further work is on the table.

Significant parts of the ITERAMS portfolio have been validated in small-scale testing at the mine sites, demonstrating the feasibility of the concept. Now, pilot demonstrations on a larger scale will be beneficial, e.g. for the use of alkali-activated materials or geopolymers in various applications. This will allow to evaluate the technology under real operating conditions.

For analysing the effects of tailings leaching, existing models proved to be too granular and too time-consuming to be computed until a point where the overall releases from the tailings can be estimated. The analysis thus needed to revert to a relatively simple emission-factor model that is not able to consider complex interactions of compounds in acid regimes. It would be very interesting to improve existing aqueous geochemical calculation tools, such as PhreeqC to reflect interaction sufficiently, within an acceptable time frame. The expected, more detailed model results would then facilitate the formulation of recipes for specific applications of alkali-activated materials and geopolymers.

A lack of water quality data currently limits a reasonable control of water quality impacts on flotation performance. The sensors and work protocol developed in the course of ITERAMS already are a considerable step forward. Still, more work would be beneficial to better integrate sensors, refine water quality models, and thereby make the flotation more effective and efficient, which in turn has direct consequences for refined process control for a mine with a closed water cycle. This would also provide the industry with capabilities to run simulations to create short-term forecasts for site's water volumes and for water quality in different production and environmental conditions, and thus would simplify mining operations' management.

For the sustainability assessment, the qualitative modelling as the first step was effective in ITERAMS for understanding the situation at each mine site, and for the more detailed, following modelling as well. It should be further established and probably structured, for different use cases. Despite a somewhat difficult time with access restrictions in force at mines, it was possible to collect sufficient data from the mine sites, for the detailed models, and to indeed reflect the quite broad modelling scope of environmental, social, and economic impacts, at the mine site and the life cycle, including risks. Now, towards the end of the project, it becomes clear that this detailed modelling can provide a relatively comprehensive, high-resolution picture of the sustainability of the ITERAMS solution portfolio in the different cases. Let's therefore wish that this detailed modeling becomes more common practice.

When looking at the detailed results, it is apparent that the ITERAMS solution portfolio does not always in itself reduce the impacts at the investigated mine sites, at times of regular operation. The risk the mine poses to its local environment, in terms of environmental, social, and also economic risks, is, however, drastically reduced. The case studies investigated in the project are already applying "some sort of water closing" technologies, independent of the project. It would therefore be interesting to apply the ITERAMS technical portfolio and also sustainability modelling approach to other cases, copper mine sites with wet processing, where the water cycle is remains relatively open.

One thing we can state with some certainty: more intelligent ore sorting at the place of excavation, due to improved analysis of the material, delivers a more tailored and efficient mine operation, generating less tailings.

APPENDIX

ITERAMS CONSORTIUM

VTT TECHNICAL RESEARCH CENTRE OF FINLAND LTD Finland

VTT Technical Research Centre of Finland Ltd is a non-profit government organization established by law and operating under the auspices of the Finnish Ministry of Employment and the Economy. VTT is a multitechnological research organization providing high-end technology solutions and innovation services.

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METSO OUTOTEC Finland

Metso Outotec provides leading technologies and services for the Sustainable use of Earth's natural resources. As the global leader in minerals and metals processing technology, the company has developed many breakthrough technologies over the decades for our customers in metals and mining industry.

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BUREAU DE RECHERCHES GÉOLOGIQUES ET MINIÈRES France

BRGM, or French Geological Survey, is the leading public institution in the field of Earth Science in France. Its main mission is to develop and improve methodologies and techniques for the management of surface and subsurface resources, through technological research and development and innovation, support to public policies and citizen information, international cooperation and development aid, and safety and monitoring of former mining sites.

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MONTANUNIVERSITÄT LEOBEN Austria

Montanuniversität Leoben is a centre for education and research and devoted to the theme "Added Value for the Future" as a central objective in its development. The research portfolio comprises the value-added lifecycle, starting with the exploration and extraction of raw materials, followed by fields such as metallurgy, high performance materials, process- and production engineering, and complemented by environmental engineering and recycling.

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FQM Kevitsa Mining

FQM KEVITSA MINING OY Finland

Kevitsa Mining Oy is a mining operation wholly owned by First Quantum minerals limited. The mine operates in Northern Finland in the Lapland province. This operation is a Cu-Ni PGE operation commissioned in 2012 and currently treats 7.2 million tons per annum of ore through the processing plant. The processing plant consists of a crushing, grinding, flotation and concentrate dewatering circuits.

Benjamin Musuku

HMT

HACETTEPE MINERAL TECHNOLOGIES LTD Turkey

Hacettepe Mineral Technologies (HMT) LTD is a spin-off company operates at Hacettepe University Technology Development Centre. It was established as an R&D company. The range of capabilities and skills of HMT research staff gives the opportunity to work on various areas of mineral processing.

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UNIVERSITY OF OULU

UNIVERSITY OF OULU Finland

The University of Oulu is an international research and innovation university engaged in multidisciplinary basic research and academic education. UO is one of the largest universities in Finland with an exceptionally wide academic base. Current research covers over 70 fields of science.

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GreenDelta

GREENDELTA GMBH Germany

GreenDelta is an independent sustainability consulting and software company located in Berlin, Germany. It combines highly professional, skilled, agile software development with profound expertise in the field of Life Cycle Sustainability Assessment and data management.

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ima engineering

IMA ENGINEERING LTD OY Finland

IMA is a privately owned company, who started as a spin-off from Outokumpu Technology Group in 1994. The unique “On-Line Mine” concept includes solutions from exploration to mining and to mill. The company IPR includes various on-line analytical technologies and products integrated with mining equipment such as drill rigs.

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AngloAmerican

ANGLO AMERICAN SERVICES (UK) LTD — United Kingdom

Anglo American is a globally diversified mining business. The portfolio of world-class competitive mining operations and undeveloped resources provides the raw materials to meet the growing consumer-driven demands of the world's developed and maturing economies.

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Aalto University
School of Chemical
Technology

AALTO KORKEAKOULUSAATIO — Finland

Aalto University, founded in 2010 as a merger of the Helsinki University of Technology, Helsinki School of Economics, and the University of Art and Design Helsinki, works towards a better world through top-quality research, interdisciplinary collaboration, and pioneering education.

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UNIVERSITY OF CAPE TOWN — South Africa

The University of Cape Town is an inclusive and engaged research-intensive African university that inspires creativity through outstanding achievements in learning, discovery and citizenship; enhancing the lives of its students and staff; advancing a more equitable and sustainable social order and influencing the global higher education landscape.

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CASPEO
Beyond process simulation

SARL CASPEO — France

Caspeo is a French SME founded in 2004, proposing advanced solutions for process analysis and optimization. Caspeo's know-how consists in process material balance engineering, process modelling and simulation, process design and optimization, sampling and measurement quality, material balance management and follow-up.

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LUT University

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY Finland

Lappeenranta University of Technology is a pioneering science university in Finland, bringing together the fields of science and business since 1969. LUT has outstanding feature of successfully integrating expertise in technology and economics.

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AMPHOS 21
Scientific and Strategic Environmental Consulting

AMPHOS 21 Spain

Amphos 21 is a scientific, technical and strategic consultancy leading with key environmental issues, particularly in the frame of waste and water management. The mining industry is at present the largest environmental market for the company.

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TEAM OF SITE B Portugal

LIST OF FIGURES AND TABLES

FIGURES

TABLES

SELECTION OF SCIENTIFIC PUBLICATIONS IN ITERAMS

Bomberg, M., Miettinen, H., Musuku, B., Kinnunen, P. *(2020) First insights to the microbial communities in the plant process water of the multi-metal Kevitsa mine. Research in Microbiology.*
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→ https://doi.org/10.1016/j.mineng.2020.106613

The complete list of publication, papers sent for review, and articles and posters in conferences can be downloaded under
→ http://iterams.eu/Home/Downloads.

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Project acronym:
ITERAMS

Project title:
Integrated mineral technologies for
more sustainable raw material supply

Start date project:
1 June 2017

Duration:
42 months

Deliverable No:
6.7

Date submitted:
Month 42