BIOMOre
An Alternative Mining Concept

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

D4.1
Report on 'Most cost effective flowsheet for an industrial scale BIOMOre operation'

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List of figures

List of tables

List of annexes

Executive summary

Introduction and Objective of this Deliverable

The BIOMOre project intends to do applied research on many of the unit operations, their parameters, and concepts that may be applicable and required for the implementation of a commercial operation in Europe for the exploitation of natural resources to produce metals or intermediate products. The unit operations for metal or product recovery from the leach solution that will be assembled into the commercial flowsheet of a potential BIOMOre operation must therefore be chosen on their merits of commercial viability, along with all the other parameters of importance, such as safety, sustainability, constructability, maintainability, operability, by-products, etc.

To ensure that BIOMOre research efforts are focussed on products and unit operations that may be used commercially, a techno-economic screening process is used to separate products and unit operations for metal recovery that have a high probability of commercial implementation from those that have a very low probability.

The objectives of this deliverable are 1) to document those elements or products and downstream product recovery unit operations that have a high probability of commercial implementation, and 2) to identify those metals/products and unit operations that can certainly not be implemented commercially with the current technology and knowledge. These would therefore be candidates for exclusion from further applied research under the BioMOre banner. From their nature, these are then also the products and unit operations that have the most to gain from further fundamental research under different projects.

The present study refers to the in-situ leach recovery of copper and optionally other elements from a copper-shale/sandstone deposit. However, the methodology can be applied to in-situ recovery from comparable deposits that meet the criteria for this specific mining technology. In particular, the present report describes the technological and economic conditions for the recovery of metals from the PLS (pregnant leach solution).

Methodology

The techno-economic screening process compares the relative incremental cost of production with the revenue of different metal and intermediate products (for example, copper cathodes and copper sulphide precipitates) for a range of suitable recovery unit operations.

The process to determine the relative costs of production involves a series of sequential steps. This methodology is commonly used by project owners and engineering companies alike for the determination of economic viability of a project, a product or a process. At a high level the sequential steps include:

- Creation of various flowsheets by logically grouping unit operations together that allow the technical recovery of metals or products from the leach solution.

- Performing mass and energy balance simulations on the various flowsheets to determine the relative flows of materials, reagents and products.

- Calculation of capital costs of the sized equipment by determining the sizes of the major mechanical equipment using the results from the mass balances and considering the purchase cost of the equipment, as well as installation costs. Calculation of the capital intensity by dividing the capital cost by the production of ten years.

- Calculation of the relative operating costs for the various flowsheets by considering the consumptions of reagents (from the mass balances) and their unit costs, an estimate of the number of staff required for the operation and maintenance of the equipment, the electricity consumption of the equipment, and the cost of maintenance spares.

- Calculation of potential revenue by using the product flows from the mass balances and an indicative selling price of each product. Historical cost data was used in lieu of future predicted values.

This study is narrowly focussed on a leach solution that can be expected from an in-situ leach operation on an ore with a composition similar to that of Polish Kupferschiefer ore. This ore is typically rich in copper and poor in most other metals. The ore grade used in this study is 1.8% copper on average, while the other metals' concentrations, except for iron, is about two orders of magnitude lower.

The main assumptions for the mass balances are:

- Mass of ore leached: 10 million tons per year,

- Copper concentration in ore: 1.8% on average,

- Open space in fractured rock: 10 % by volume,

- Leach solution circulation rate: One volume exchange every five days,

- Copper leach rate: 10% per year,

- Leached solution copper concentration: 4 gram copper per liter,

- Copper production: 18 000 tons per year,

- Zinc available in solution for recovery: 200 tons per year,

- Nickel available in solution for recovery: 30 tons per year,

- Cobalt available in solution for recovery: 40 tons per year,

- Rhenium available in solution for recovery: 400 kilogram per year.

Results

The table below provides the summarised results from the comparisons of the various flowsheets based on indicative revenue, incremental operating costs and relative capital intensity.

Table 1 : Summary of revenue, operating costs and capital costs of the products and unit operations for various flowsheets based on a primary recovery unit operation. The right hand column gives an indication of whether the product and unit operation can be economical, near-economical or definitely uneconomical.

Process	Product	Revenue	Operating Cost	Capital intensity	Economical?
		€ per ton product	€ per ton product	€ per ton product	Yes/NO
Sequential Sulphide Precipitation					
Copper sulphide precipitation	Copper sulphide	4 000	1 390	203	Yes
Zinc sulphide precipitation	Zinc sulphide	1 360	4 713	10 035	No
Nickel/cobalt sulphide precipitation	Mixed nickel cobalt sulphide	8 500	4 294	33 525	No
Recovery by Ion Exchange					
Copper by IX/EW	Copper cathodes	4 800	613	168	Yes
Copper by IX and sulphide precipitation	Copper sulphide	4 000	1 997	203	Maybe
Zinc by IX/EW	Zinc cathodes	1 600	5 771	6 612	No
Zinc by IX and sulphide precipitation	Zinc sulphide	1 360	10 484	15 005	No
Nickel/cobalt by IX and EW	Nickel cathodes	10 000	N/A	36 392	No
Nickel/cobalt by IX and sulphide precipitation	Mixed nickel cobalt sulphide	8 500	19 343	59 900	No
Nickel/cobalt by IX and carbonation	Sintered nickel briquettes	10 000	N/A	52 772	No

Process	Product	Revenue	Operating Cost	Capital intensity	Economical?
		€ per ton product	€ per ton product	€ per ton product	Yes/NO
Nickel/cobalt by IX and hydroxide precipitation	Mixed nickel cobalt hydroxide precipitate	8 000	>20 000	46 200	No
Recovery by Solvent Extraction					
Zinc by SX and EW	Zinc cathodes	1 600	>20 000	8 984	No
Zinc by SX and sulphide precipitation	Zinc sulphide	1 360	>24 000	17 378	No
Copper by SX and EW	Copper cathodes by EW	4 800	609	173	Yes
Iron(III) solution by SX for re-use in bioleach	Iron(III) solution for re-use in bioleach	-	>1 000	1 505	No
Iron hematite precipitate in autoclave	Iron hematite precipitate	-		2 645	No
Nickel by SX and EW	Nickel cathodes	10 000	Note[1]	143 000	No
Nickel/cobalt by SX and sulphide precipitation	Nickel/cobalt sulphide	8 500	>28 000	160 000	No
Nickel/cobalt by SX, carbonation, reduction and sintering	Nickel briquettes	10 000	>20 000	183 000	No
Nickel/cobalt by SX and hydroxide precipitation	Mixed nickel/cobalt hydroxide	8 000	>20 000		No

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1) The nickel elution solution, though pure, is only about 1 g/L concentration in this case, which is not concentrated enough for electrowinning, and therefore electrowinning is not a real technical option for this BIOMOre ore.

Process	Product	Revenue	Operating Cost	Capital intensity	Economical?
		€ per ton product	€ per ton product	€ per ton product	Yes/NO
Recovery by Cementation					
Copper by cementation with zinc dust	Copper briquettes	4 460	2 800	300	Probably not
Redissolution of copper cement and sulphide precipitation	Zinc sulphide powder	1 360	2 231	10 035	No
Rhenium from IX					
Rhenium from IX, evaporation and recrystallization	Rhenium metal	2 000 per kilogram		15 600 per kilogram	No

Conclusions

From the results above it can be concluded that copper has a high probability of being recovered economically from this ore using any of the unit operations for downstream recovery. However, this study is deliberately silent on whether a commercial operation based on BIOMOre technology can be economically attractive, and the reason is that this study evaluated incremental costs and incremental revenue alone. A full feasibility study is required to determine the viability of the overall process.

For the flowsheet based on sulphide precipitation as the primary recovery method, copper is the only product that can be recovered economically. The incremental operating costs for recovering zinc exceed the incremental revenue. Though the operating cost for a nickel and cobalt product is below the incremental revenue, the capital intensity of the equipment is such that this product cannot be recovered economically.

For the flowsheet based on ion exchange as the primary recovery method, copper is the only product that can be recovered economically, and only by ion exchange (IX) followed by electrowinning (EW). IX followed by sulphide precipitation may be economical, however, sulphide precipitation is normally well suited for low concentrations or low production volumes. The incremental operating costs for recovering zinc exceed the incremental revenue, irrespective of the recovery methods. For nickel and cobalt products the capital intensity of the equipment far outweighs any incremental revenue for all four combinations tested.

For the flowsheet based on solvent extraction as the primary recovery method, copper can be recovered economically. This result has to be expected since nearly all commercial copper hydrometallurgical circuits are based on SX and EW. Zinc cannot be recovered economically because the incremental operating cost is much higher than the incremental revenue, and also because of excessive capital intensity. Recovering an iron solution is probably not economical, and recovering iron as hematite via any autoclave process is ruled out based on excessive capital intensity. For nickel and cobalt products the capital intensity of the equipment far outweighs any incremental revenue.

Copper recovery by cementation is probably not cost effective, due to the large amounts of zinc dust consumed in the process.

Though elegant technology exists for rhenium recovery, it cannot be recovered economically based on the excessive capital intensity of the equipment.

In summary, if BIOMOre technology is applied to Kupferschiefer ore (Cu shale and underlying sandstone) then copper should be recoverable economically by a variety of methods. The most cost effective method will depend on the concentration of copper in solution. As the ore is poor in many other elements, hardly any other individual metal product may be recovered economically. One potential focus area for this project can therefore be the development of recovery methods for a combined by-product mix that can be stored separately from waste products with the aim of future recovery once economic methods become available. Another focus area can be the development of an economical iron removal process.

Content

1. Introduction

The intended outcome of the BIOMOre project is the implementation of an operation in Europe for the exploitation of natural resources for the commercial production of metals or intermediates on a for-profit basis. The unit operations that are assembled into the commercial flowsheet of a potential BIOMOre operation must therefore be chosen on their merits of commercial viability, along with all the other parameters of importance, such as safety, sustainability, maintainability, operability, by-products, etc. This report deals with the unit operations specifically for downstream metal recovery from solution, and does not address the flowsheet options for the leaching steps or solution inventory sequencing or control.

Many unit operations exist for the recovery of valuable products from solutions. The BIOMOre process uses an acidic bioleach solution for leaching of underground metals, and is expected to generate a solution that potentially contains several valuable products. To ensure that research efforts are directed towards enhanced understanding of processes and unit operations and products that have practical economic application within the BIOMOre process, those processes with potential application on economic scale need to be identified and studied. Simultaneously, those processes and potential products with a slim likelihood of being incorporated into an overall economic processing flowsheet should be identified early on so that applied research efforts can be focussed on adding value to high potential processes instead.

This document presents the results from a techno-economic study whereby existing proven technologies for recovery of potentially valuable products from BIOMOre solutions are compared and ranked on the basis of their :

- Ongoing processing costs, such as the cost of reagents and consumables, electricity, personnel to operate and spares to maintain the processing equipment,

- Capital costs for the processing equipment,

- Quantity of product and the market value thereof.

For combinations of unit operations to be potential candidates for incorporation into the flowsheet of an industrial scale BIOMOre project, such combinations of unit processes and their products must be economically feasible, or at least have the potential to be economically feasible. Further applied research on such processes can then potentially focus on improving the environmental footprint, reducing waste disposal requirements, improving extraction efficiencies, reducing water requirements, reducing chemical requirements, making more benign waste products, extracting value from by-products, improving safety aspects or sustainability, or simplification of skillset required for operation and maintenance.

2. Methodology

The methodology used in this study entails the techno-economic comparison of a selection of unit operations or processes that can be used for the recovery of metal-based products from a BIOMOre-type leach solution.

The revenue of a unit operation is determined from the quantity of the product times the potential market value or selling price thereof. The ongoing operating cost of producing such product is then factored into the economic model. Repayment of the capital cost required to construct facilities for the recovery of the product is also factored into the economic equation. This technique is commonly used in the mining, metallurgical, process and chemical industries for comparing unit operations to select the most suitable ones.

The unit operations are compared on their relative potential to add value to an industrial processing facility. The value-add is on a relative basis, not on absolute value basis. While the costs, both operating and capital, are calculated for the combinations of the unit processes, the total capital and operating costs for the entire processing facility are not developed in this study. This way the unit operations that are identified as adding value or having the potential to add value are recommended to be selected for further research to enhance their value to the BIOMOre project. Similarly, those unit operations that clearly do not add value, by virtue of their costs far outweighing the market value of the product, are candidates for excluded for consideration. Also, unit operations with marginal economic benefits are not excluded, and indeed may even benefit from further research.

To make this comparison, each unit operation's equipment first has to be sized and designed for use on industrial scale, followed by the calculation of the capital cost of purchasing the equipment and assembly thereof into a coherent processing facility. The capital cost is commonly amortised to determine the relative capital intensity of the unit operation. Tax and other financial instruments are not included in this comparison, based on the premise that such financial instruments will be applied consistently across all selected unit operations and as such will not contribute to differences in the costs or value of the unit operations.

To determine the costs, a base case option is chosen for the size of the processing facility, also known as the throughput of the processing facility. The next paragraphs provide the base case data and major assumptions to assemble the cost study.

2.1. Processing Parameters

2.1.1. Scale Of Operation

A base case operation was selected with 10 million tons of ore per year to be leached by ferric solution.

2.1.2. Ore Composition

The ore composition will necessarily depend on the ore body chosen for the implementation on industrial scale. For example, if the process was implemented in a location with a Kupferschiefer ore[2] with the main minerals of interest being copper minerals, then the following mineral composition may be applicable.

Table 2 : Composition of hypothetical Kupferschiefer ore[3,4]

Element	Concentration
Copper	1.8 – 5.5 %
Zinc	0.02 % - 0.05 %
Nickel	30 – 100 g/t
Cobalt	40 – 150 g/t
Rhenium	0.4 – 1.1 g/t
Molybdenum	20 – 140 g/t

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2) Kupferschiefer, or "copper shale," is a thin carbonaceous marly shale layer at the stratigraphic boundary between the Lower Permian (Saxon) and Upper Permian (Zechstein) strata. This layer hosts one of the biggest accumulations of sediment-hosted copper worldwide. The unit is overlain by the Zechstein limestone and underlain by the Weissliegend sandstone; it is most well known in Germany and Poland. Several historic (Germany) and currently active Lubin mining districts (Poland) with significant ore bodies and widespread sub-economic mineralisation occur as an intermittently developed E-W-trending belt along the central part of the southern margin of the Kupferschiefer basin.

3) Vaughan, DJ, Sweeney, M, Friedrich, G, Diedel, R, Haranczyk,C (1989). "The Kupferschiefer: An Overview with an Appraisal of the Different Types of Mineralization", Economic Geology, Vol. 84, 1989, pp. 1003-1027.

4) Porter Geoconsultancy (2015). Kupferschiefer-Zechstein, Lubin, Rudna, Sieroszowice, Polkowice, Glogow, Konrad, Lena, Nowy Kosciol, Poland. http://www.portergeo.com.au/database/mineinfo.asp?mineid=mn401 (accessed 15 April 2015).

Element	Concentration
Arsenic	200 – 500 g/t
Vanadium	30 – 150 g/t
Lead	0.01 – 0.7 %
Silver	80 – 130 g/t

2.1.3. Estimate Of Liquor Composition

To calculate the probable liquor composition a mass balance over the in-situ leach and the downstream removal of metals from solution was developed. Major assumptions are that:

- Copper concentration in the ore is about 1.8%,

- About 10% to 30% of the copper will leach over a year, average 10%,

- Metals or products will be recovered from a side stream of 15% of the recirculating solution, and that the depleted solution will rejoin the remainder of the circulation stream after fortification,

- 10 million tons per year ore leached (as per 2.1.1),

- 3 gram per litre free sulphuric acid in the leaching solution,

- Zero liquor loss to surrounding rock, and

- Solution make-up equivalent to the volume removed in product recovery,

- 10% open volume in rock mass, and

- In-situ solution replenished every 5 days.

The US Bureau of Mines' experimental in-situ leaching of copper using sulphuric acid from a buried porphyry deposit at Casa Grande, New Mexico reputedly yielded negligible recoveries.[5] The same reference reported that at the San Manuel in-situ operation in Arizona, recovery rates of copper from hard rock caved areas already mined was estimated of the order of 50% to 60% over five years. The assumption in this report of 10% copper extraction over a year therefore seems to be reasonable. It must be noted here that the choice of absolute value is not critical in this study, because all the unit operations are compared one to another on a relative basis. Uranium in situ leach operations typically achieve higher dissolution values. However, recoveries from uranium in situ leaching operations in sandstone are not

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5) O'Gorman, G, von Michaelis, H, and Olson, G,J. Novel In-Situ Metal and Mineral Extraction Technology, Final Report, 9/30/03 through 9/22/04. Report Issued: September 22, 2004.

relevant to this study about leaching copper sulphides using ferric sulphated from hard rock ore bodies.

The product solution (commonly referred to as PLS) concentration depends on several kinetic and thermodynamic requirements, such as pore volume exchange rate, kinetic rate of copper leaching, and the concentration of ferric iron in the injection solution (measure of oxidation potential). With a mass balance based on these assumptions the copper concentration in the product solution is about 4 g/L. With slightly different assumptions the copper concentration can vary between 1.5 g/L and 5 g/L. The zinc concentrations are expected to be at least two orders of magnitude lower (likely in the concentration range of 0.05 g/L), and cobalt yet another order of magnitude lower. Other elements may be present is smaller or nuisance quantities.

2.2. Capital Cost Of Equipment

There are numerous characteristics that can be used to categorise cost estimate types. The most significant of these are degree of project definition, end usage of the estimate, estimating methodology, and the effort and time needed to prepare the estimate. The "primary" characteristic used by the Association for the Advancement of Cost Engineering (AACE[6]) to define the classification category is the degree of project definition. The other characteristics are "secondary."

Categorising cost estimates by degree of project definition is in keeping with the AACE International philosophy of Total Cost Management, which is a quality-driven process applied during the entire project life cycle. The discrete levels of project definition used for classifying estimates correspond to the typical phases and gates of evaluation, authorisation, and execution often used by project stakeholders during a project life cycle. While the level of project definition is a continuous spectrum, it was determined from benchmarking industry practices that five discrete categories are commonly used. The estimate class designations are labelled Class 1, 2, 3, 4, and 5. A Class 5 estimate is based upon the lowest level of project definition, and a Class 1 estimate is closest to full project definition and maturity.

For this level of study, it is appropriate to build up the total capital cost estimate by using factors on top of the costs of the major process equipment to determine the total installed cost of such equipment. This methodology results in an AACE Class 5 estimate, which normally has an accuracy of ±50%.

The major process and mechanical equipment for each technology and associated unit operations was sized from first principles based on the mass balance flows.

Costs for the major process and mechanical equipment were sourced using a number of methods. The costs for the majority of equipment were sourced from the

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6) Association for the Advancement of Cost Engineering International.

Hatch database that contains equipment costs from recently completed projects. Costs were updated for material of construction, currency, escalating, inflation and current market conditions. In addition to this, vendors were consulted for specific equipment costs involved in the process.

For this specific study relative capital costs are calculated for the unit operations' equipment only on a common basis and for the boundary limits of the unit operations, so that the costs of each can be compared to each other. This comparative costing thereby allows the unit operations to be compared and ranked relative to each other.

2.3. Operating Costs

The direct operating costs for a unit process is customarily calculated from the consumption and costs of chemicals and reagents used by the process, the incremental cost of personnel to operate the process, the electricity consumption and the cost of maintaining the equipment. This methodology allows the operating cost of one unit operation to be compared to that of another.

The reagent consumptions are derived from the mass balances for each flowsheet option. The unit costs of main reagents are the Q3 market costs, while the unit costs of minor chemicals come from Hatch database costs of 2015. An estimate, based on experience with projects of similar nature, is made of the number of incremental staff to operate the unit operations under consideration in each case. The electricity consumption is derived from the power draw of the main process equipment of the unit operations. The electricity unit cost is the average cost charged to industrial consumers in the Lubin mining district (about €0.10/kWh). The maintenance cost of the equipment for the unit operations is estimated as 10% of the direct capital cost of the equipment. Disposal costs have not been included.

2.4. Market Value

The revenue of a product is normally calculated from the quantity of the product multiplied by the selling price of the product. The selling price depends on the nature of the product, for example, whether the product is a final or intermediate product. In the mining and minerals industries a final product is normally regarded as one that can be sold directly to the manufacturing industries, for example a metal product such as copper or zinc metal. An intermediate product on the other hand, is a product that needs further processing before it can be sold to manufacturing. Examples of such products are copper sulphide, zinc sulphide, mixed nickel/cobalt hydroxide precipitate (MHP), copper sulphate, to name a few.

The selling price of metal products is taken to be the London Metal Exchange (LME) price in Q3 of 2015. For intermediate products, like sulphides, the selling price was taken as a percentage of the LME metal price, nominally 80% or 85%, depending on the requirement for further processing to obtain a metal product.

This study concerns with the process from mining to marketable product, and does not consider downstream processing of mining products. Normally downstream processing has smaller margins than mining and extraction. Most mining and processing operations sell a primary product, and this study is concerned only with selling finished primary products, or intermediates, but not end-user products.
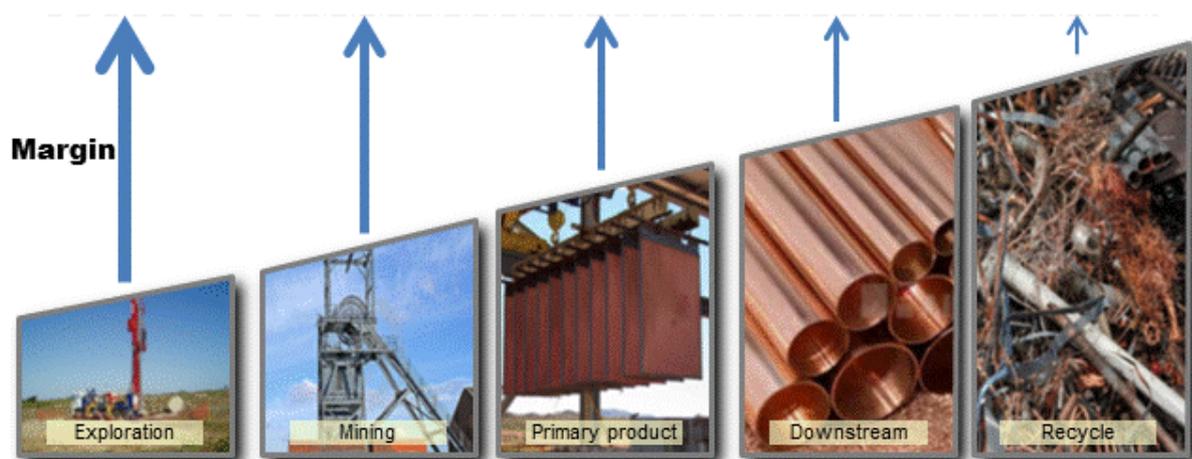
Figure 1 : Pictogram showing the margin of the phases of a commodity such as copper.

Note : The higher the margin (left hand side) the more capital investment is possible. The stages on the right hand side have lesser margins and therefore these phases cannot tolerate large investments. This study covers the production or primary products only. Downstream processing is typically not performed by mining operations.

2.5. Unit Operations and Combinations Thereof

For this study only unit operations that are suitable for the recovery of the metals of commercial interest in BIOMOre solutions are considered. To be considered, the unit operation must be suitable for recovering or purifying metals from solutions containing low to very low concentrations of metals. The BIOMOre solution is expected to be dilute, i.e. have low or very low concentrations of all metals except copper. A typical example of a unit operation that is technically suitable to remove dissolved metals at low concentrations economically at an industrial scale is ion exchange, whereas electrowinning is an example of a unit operation that is suitable only to high concentrations on an industrial scale, inherently because of low current efficiencies and exceptionally high capital cost requirements for low concentrations. Though unit operations may work in the laboratory, the acid test here for inclusion as a candidate for consideration is whether the unit operations have been applied commercially on an industrial scale.

Also, with the industrial implementation of BIOMOre technology intended to occur within the foreseeable future, say within five years, only unit operations suitable for recovery of metals or products that have already been industrialised have been selected for this study. The rationale is that the development of a new unit operation from concept and laboratory work, through to piloting, engineering and construction of a demonstration scale unit, followed by the design, engineering and construction of a full scale facility typically takes about ten years, thereby missing the window of opportunity for BIOMOre implementation. This does not imply that new and novel processes should not be researched, only that these are not recommended to be included as candidates for this phase of the project.

Many unit operations are routinely used in the laboratory. Many of these have not found industrial implementation, either because these processes are too costly or too complex to implement economically, or the equipment require too much maintenance, or the process requires too much water, or for other reasons. An example of such a technique includes dilute-phase electrowinning, evaporation, diffusion dialysis, or electrodialysis. These processes are not considered in this study as candidates to evaluate for economic implementation on industrial scale.

Unit operations with proven track records on industrial scale for the separation of copper, zinc, nickel, cobalt or gypsum from sulphate solutions selected for studying as potential candidates for incorporation into cost-effective flowsheets for an industrial scale BIOMOre operation include:

- Sulphide precipitation at atmospheric pressure, for copper, zinc, nickel and cobalt,

- Ion exchange for copper and zinc,

- Solvent extraction for copper, zinc, nickel and iron,

- Cementation of copper by zinc powder,

- Jarosite precipitation for iron removal,

- Hematite conversion under pressure, and

- Gypsum precipitation.

Many processes are available for iron removal. As bulk iron is normally produced most cost effectively from iron ore, nuisance quantities that may require removal in a potential BIOMOre application have very little chance of being economical as iron or steel, unless the final end product is a speciality chemical such as paint pigments or similar. This study does however not concern itself with the unit operations for making fine chemicals in small quantities, but rather focusses on unit operations for making bulk products, in line with the business model of mining companies that would typically employ BIOMOre technology.

Most of the processes listed above individually produce concentrated solutions with relatively good purity, not final products, and therefore another unit operation is

required to make a marketable bulk product out of the solution. Typically electrowinning is a suitable technology to make a metal product, or sulphiding to make a metal sulphide product. Precipitation as a hydroxide is also used sometimes, notably for nickel.

Some of these unit operations produce products that are not final end-products, such as the copper or zinc sulphide by precipitation; however, this study does not consider the downstream refining of products or the downstream manufacturing of products. Typically mining companies do not diversify into manufacturing of end products, but rather sell marketable bulk products, and therefore this study is concerned only with unit processes that can result in making marketable bulk products.

Though many other unit operations are commonly employed in the laboratory to demonstrate the conversion of one product to another, many of these techniques haven't found industrial implementation as yet, principally based on unfavourable economics. The high temperature and high pressure conversion of jarosite into hematite in an autoclave is included in this study to demonstrate the economics of such an operation on industrial scale.

Most of the above unit operations don't produce a marketable bulk product on their own, and therefore some of the operations need to be daisy-chained to produce a marketable bulk product. For example, solvent extraction of, say copper, produces a reasonably concentrated solution of copper sulphate, and to get a final marketable bulk product this solution needs to be treated with either a crystalliser to produce copper sulphate crystals, or be treated with electrowinning to produce metal sheets.

A graphical depiction of all the flowsheets considered is given in Annex A.

2.5.1. Sulphide Precipitation

Sequential sulphide precipitation is suited well to dilute solutions containing ferrous iron, copper, zinc, nickel and cobalt. This process has found industrial application, notably at Talvivaara.

On a high level the Talvivaara flowsheet can be applied to a BIOMOre solution. In this flowsheet, the solution is passed through a series of continuously stirred tank reactors (CSTRs) while a sulphiding agent, typically hydrogen sulphide gas, is added stoichiometrically to precipitate the copper as copper sulphide. The resulting slurry now contains copper sulphide solids and is thickened. The thickener underflow containing the sulphide solids is filtered and washed to recover the sulphide product. The product is dried and packaged for the markets. Meanwhile, the thickener overflow solution is sulphided again in another series of CSTRs, this time to recover zinc sulphide. The equipment types are the same as for copper sulphide. The resulting slurry is thickened again, filtered, washed, dried and prepared for the markets.

The solution, now barren of copper and zinc may be processed for nickel if it is present in commercial quantities. For this, the pH is raised a little, typically using sodium hydroxide, and thereafter the solution is again contacted with hydrogen sulphide to precipitate nickel and cobalt. Similarly to above, the nickel sulphide is thickened, filtered, washed, dried and prepared for delivery to markets.

The barren solution from sulphiding essentially contains all the iron, as ferrous iron. Depending on the original amount of iron dissolved from the ore by the ferric leaching solution, this iron may be returned to the bioreactor after pH adjustment to oxidize it to the iron(III) form for re-use as lixiviant, or it may need to be disposed of. In this case oxidation and precipitation may be considered. Various unit operations exist for this, and the costs of these are not considered here as part of the recovery of copper, zinc, nickel and cobalt.

2.5.2. Ion Exchange

Ion exchange is one of the unit operations that excel at removing dissolved metals from dilute solutions. The BIOMOre solution is expected to be dilute.

On a high level, one ion exchange flowsheet that can be applied to a BIOMOre solution is that of firstly passing the solution (at its natural pH, expected between pH 2 to about pH 3) over a resin such as DOW XUS-43605 that selectively adsorbs copper and that lets iron, zinc, nickel and cobalt pass through. The resin is eluted to yield a relatively concentrated copper solution. This solution may be suitable for copper recovery by electrowinning or sulphiding.

The barren solution from the first stage ion exchange is passed over another ion exchange resin that lets the iron through while adsorbing zinc, nickel and cobalt. Zinc is eluted selectively from the loaded resin by 20 g/L sulphuric acid, and nickel is eluted thereafter with 200 g/L sulphuric acid. The zinc elution cycle produces a relatively concentrated solution of zinc (about 3 to 5 g/l), while nickel elution produces a solution with about 0.8 g/L nickel concentration. These may be treated further by sulphiding to recover metal sulphide products, or with electrowinning to recover metals.

The barren solution essentially contains the iron and similarly to above under sulphide precipitation, the iron may be returned or it may need to be disposed of. Again the costs are not considered here in the comparison of unit operations for the recovery of copper, zinc, nickel and cobalt.
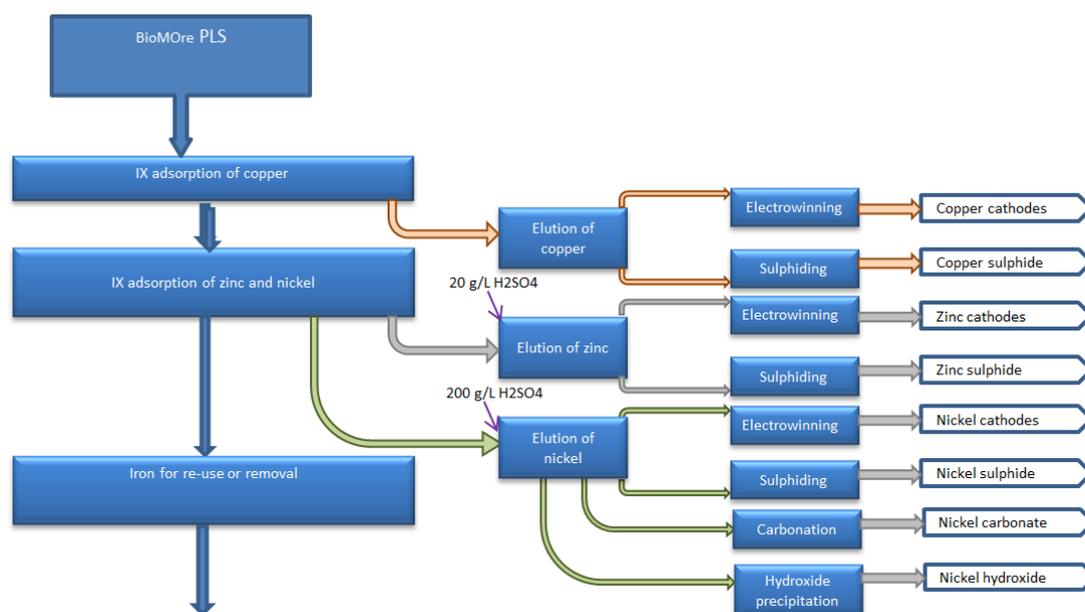
***Figure 2 : Combinations of unit operations to produce products from ion
exchange as the primary unit operation.***

For this study the capital costs of the equipment in the processing facilities and the
operating costs of the unit operations are based on the processing flowsheets of
Figure 2.

2.5.3. Solvent Extraction

Solvent extraction is normally the unit operation of choice on industrial scale for
solutions that are not too dilute, typically when the concentration of metal is several
grams per liter. When the solutions are too dilute the capital cost of equipment and
operating costs of reagents become prohibitively expensive and alternative unit
operations are normally employed industrially.

On a high level, a solvent extraction flowsheet that can be tailored to a BIOMOre
solution is that of sequentially extracting zinc, copper, iron, and nickel. The individual
product streams coming from solvent extraction are normally of high concentrations.
Several arrangements and combinations of extractants are available to the process
engineer to choose from to optimise the circuit. As an option study of the most
economical sequence of extraction is beyond the scope of this report, one
arrangement that works effectively is chosen for this study.

In this flowsheet the incoming BIOMOre solution pH is adjusted to about 1.6 with
sulphuric acid and contacted with organic solvent extraction chemicals in two
extraction stages to load zinc onto the organic phase. The organic phase is stripped

with 2M sodium hydroxide to produce a loaded electrolyte solution containing more than 100 g/L zinc, suitable for electrowinning.

The raffinate from the second zinc extraction stage is contacted with a different set of organic chemicals, again in two stages, to extract copper from solution. The organic phase is stripped of copper with strong sulphuric acid to yield a solution of about 60 g/L copper, again suitable for electrowinning or sulphide precipitation.

Next iron is removed from the copper raffinate by contacting with organic chemicals in a single stage. The organic phase is stripped with weak sulphuric acid to yield an iron sulphate stream.

The iron raffinate stream's pH is adjusted to about 5.5 with sodium carbonate and is then contacted with another set of organic chemicals to extract nickel from the solution. The nickel is stripped with strong sulphuric acid to yield a loaded electrolyte, suitable for electrowinning, or other recovery method.

The nickel raffinate contains very little other metals of interest, and can essentially be re-used as makeup for the ferric leaching solution, or treated via waste water methods and discarded, depending on the requirements of the integrated mass balance of a commercial operation.
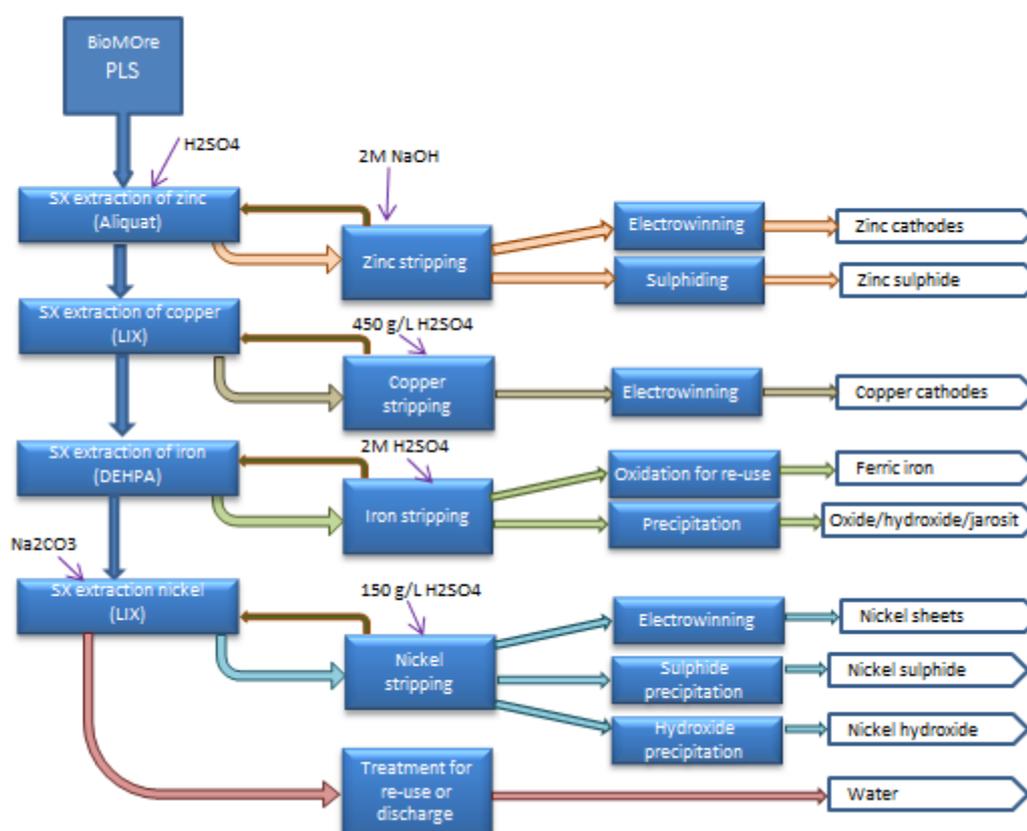
Figure 3 : Combinations of unit operations to produce products from solvent extraction as the primary unit operation.

2.5.4. Cementation

Cementation is used commercially in zinc hydrometallurgical flowsheets for removing copper from zinc solutions, and cementation is also commonly used to remove impurities from solutions. Copper cementation by iron is employed widely in African copper plants. A typical example of cementation used for impurity removal is the cementation of cadmium by zinc powder.

For the BIOMOre process and in a situation where there is no appreciable nickel and cobalt dissolution, copper can be removed by cementation using zinc powder, after adjusting the pH of the solution and applying solid-liquid separation. A stoichiometric excess of zinc powder is used, after which the copper/zinc cement is separated from the liquor, and the excess zinc is redissolved from the cement, thereby leaving copper sponge. In this study the copper sponge is briquetted into a final marketable product.

2.5.5. Iron Removal

Many methods exist for iron removal from solution. On an industrial scale the unit operation selected for iron removal normally depends on the end product that is required, on the cost of the producing the end product, the market value of the product, the size and proximity to a market for the product, the cost of disposal, the availability of area for disposal, the quantity and chemistry of the impurities, etc.. This study does not provide a treatise on the subject of iron removal, instead the interested reader is referred to the open literature and to proceedings of symposia dedicated to iron removal, for example the International Symposium series on Iron Control in Hydrometallurgy.

For this study on comparative costs for the separation of metals from solution, costs are provided for the hydrothermal conversion of jarosite to hematite.

3. Potential Revenue from Elements in Bioleach Solution

The contained economic value of an orebody is determined to a large extent by the ore composition and the treatment methods. The ore composition will necessarily be determined by the ore body chosen for the implementation on industrial scale. For example, if the process was implemented in a location with a Kupferschiefer ore with the main minerals of interest being copper minerals as per Table 2, and with the estimated ranges of main metals' dissolution via ferric leaching, then the quantities of products that can potentially be recovered from a BIOMOre product solution are given in Table 3, together with the economic value[7] of the products.

Table 3 : Potential quantities of metals-of-interest in solution and their revenue.

Element or Product	Quantity (tonnes per year)	Indicative selling price €/t	Revenue of recovered product (if recovered as the *metal*[8]) (€ million per year)	
			Low range	High range
Copper	18 000 to 55 000	4 800	86	264
Zinc	200 to 500	1 600	0.3	0.8
Nickel	30 to 100	10 000	0.3	1.0
Cobalt	40 to 150	25 000	1.0	3.8
Rhenium	0.4 to 1.1	2 000 000	0.8	2.2
Molybdenum	20 to 70	22 500	0.5	1.6
Arsenic	0 to 500	1 400	0	0.7
Vanadium	30 to 150	44 000	1.3	6.6
Lead and Silver	Not soluble in bioleach liquors	-	-	-
Iron and Aluminium	Not considered economical at this scale	-	-	-

7) Revenue is defined here as the quantity of a product times the selling price of the product. It does not include the cost of acquisition, the production of the product, or any other costs.

8) If the product recovered is not the metal but rather an intermediate product, such as an oxide or sulphide or alloy (eg. zinc oxide, zinc sulphide, or ferronickel) then the revenue is generally less than that of the refined metal. In this case the revenue in the above table will be less than those numbers given in the table.

From the revenue estimates it is seen that copper will be the main metal of interest with a potential revenue of between € 86 million and € 264 million. Other metals with potential values of about two orders of magnitude below copper are cobalt, vanadium and rhenium. It is unlikely that these and the other lesser products that the cost of recovery of these elements or the products containing these elements, can be economically feasible. Proof of this is provided in sections 4 and 5.

Lead and silver will not dissolve under BIOMOre leach conditions and will therefore not be recoverable from solution.

Iron and aluminium are not considered as economically viable elements for this study, particularly since industrial scale operations for these metals or ores are typically very large (hundreds of thousands of tonnes product per year) to be economical, not a few hundred tons.

Note that there is considerable variation in selling price of metals over time, as depicted in Figure 4 and Figure 5. The values used in this report are for Q3 2015.

Description: Copper, grade A cathode, LME spot price, CIF European ports, Euro per Metric Ton

Unit: Euro per Metric Ton
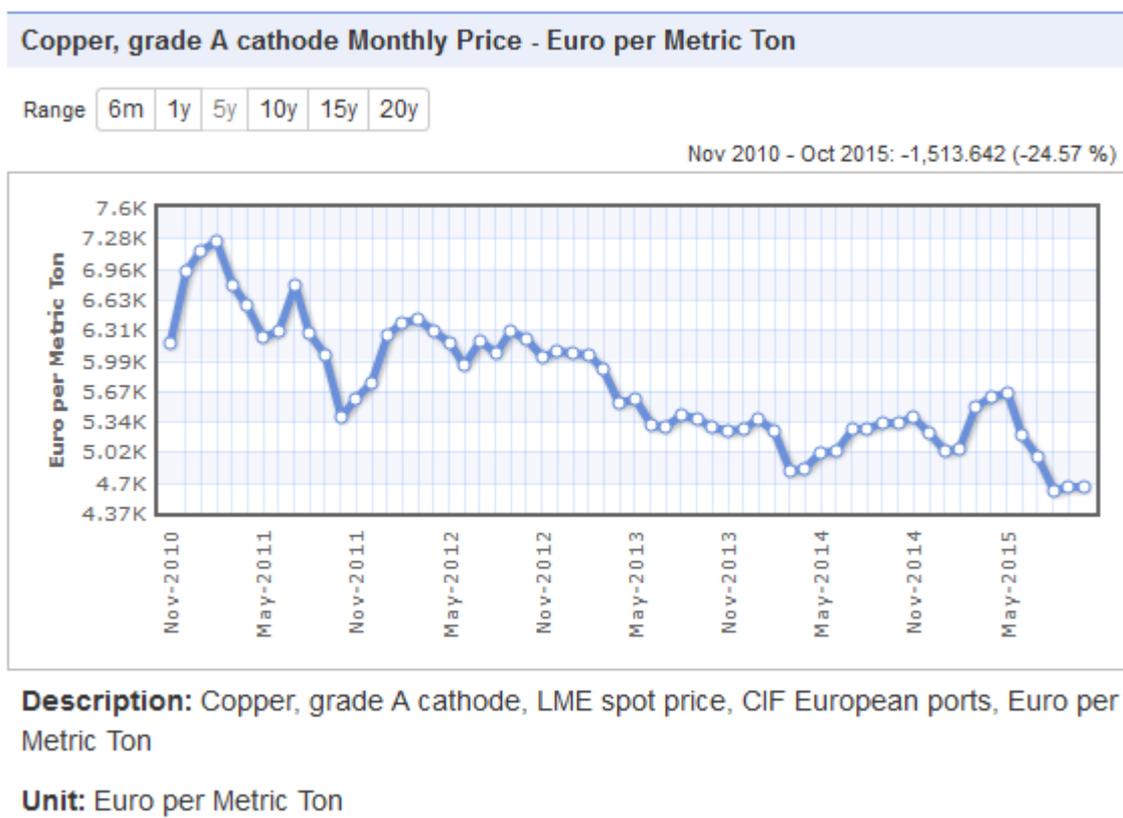
Figure 4 : Historical price of copper.

Description: Zinc, high grade 98% pure, Euro per Metric Ton

Unit: Euro per Metric Ton

Figure 5 : Historical price of zinc.

4. Operating Cost Comparison

In any commercial production facility, such as a car factory, or paint factory or metals production facility, or a commercial scale BIOMOre installation, the revenue generated from the selling of the products must be in excess of the total cost of producing such products. If not, the commercial facility is not economically viable.

Operating costs in the mining and metallurgical industries are normally expressed as C1, C2 and C3 costs. C1 costs are the net direct cash costs, C2 costs additionally include depreciation, depletion and amortisation, while C3 costs are the fully allocated costs and typically also include corporate overhead costs, R&D costs, royalties, interest charges and any extraordinary costs such as those incurred because of unexpected shutdowns or strikes.

In the case of a commercial BIOMOre installation the C1 costs are meant to cover:

- All aspects of mining (drilling, stimulation, solution pumping, solution ponds, etc.).

- All aspects of the hydrometallurgical complex (bioleach reactors, product or metal recovery, reagents, electricity, staff, maintenance, etc.).

- All infrastructure operating and maintenance costs.

- Any tailings facility, if applicable, and discharge costs.

- All general and administration expenses (G&A).

- Marketing costs (freight and selling).

To determine the total operating costs of the hydrometallurgical complex, the costs for all the unit operations of the hydrometallurgical complex are normally added up. This study, on the other hand, analyses the cost of only the unit operations that are required for metal or product recovery, i.e. only a fraction of the C1 costs are analysed. It therefore follows that the total cost of recovery (from mining, balance of hydrometallurgical plant, infrastructure, G&A and other costs) will be much higher than the cost of just the unit operations involved in product recovery.

This study compares the operating costs of various unit operations for the recovery of metals from leach solution so that a ranking can be made on the suitability of including such unit operations into a commercial scale plant. This comparison is required to select only those unit operations that have a reasonable chance of being used in a profitable commercial scale BIOMOre operation, and to eliminate those unit operations that are successful in the laboratory but are not considered to be potentially profitable on commercial scale.

Operating costs are compared for the unit operations of product recovery alone, meaning that the operating cost associated with the rest of the mine and hydrometallurgical complex are considered to be equal, irrespective of choice of metal recovery unit operation. This is a reasonable position – it is easy to understand

that the costs of drilling, stimulation and solution pumping and those costs associated with infrastructure maintenance (such as roads or buildings or offices) and marketing are not influenced by the selection of specific unit operations for product recovery.

The direct operating costs for the specific unit operations or combinations thereof are given in the following sections.

For reference, the operating cost baseline is June 2015 and the costs exclude forward escalation. These operating costs were derived with a methodology consistent with an order of magnitude study, and with an overall equipment utilisation of 90%.

4.1. Sulphide Precipitation as the Primary Recovery Method

The relative operating costs as calculated by the methodology described in section 2.3 are given in Table 4. In this specific case the products are the metal sulphides, i.e. copper sulphide, zinc sulphide, mixed nickel and cobalt sulphide and iron sulphide. Rhenium, molybdenum, arsenic and vanadium are not recovered as individual products; their concentrations are low that the equipment to provide the required contact between the solution and the sulphiding agents becomes prohibitively expensive.

Table 4 : Operating costs (annual and unit) of unit operations to produce metal sulphide products.

Process	Annual Cost € millions per year	Unit Cost € per ton metal
Copper sulphide precipitation	25.1	1 390
Zinc sulphide precipitation	0.9	4 713
Nickel/cobalt sulphide precipitation	0.2	4 294

The annual cost of just the unit operations involved in the sulphide precipitation of copper sulphide is over € 25 million per year, while that of zinc sulphide and mixed nickel cobalt sulphide is less than a million Euros per year. The amount of copper precipitated is substantial and therefore the unit cost is relatively low, as seen in the right hand column.

For zinc and nickel/cobalt the unit cost of the products is very high principally because of the low quantity of product.

It can be seen that the operating costs of just the unit operations to recover zinc sulphide are higher than the selling price of zinc given in Table 3. If all the other C1 costs are added to obtain the total cost (mining, balance of hydro-metallurgical plant, infrastructure, G&A and other costs) then it is clear that zinc cannot be recovered economically from an ore with this composition using sulphide precipitation technology.

A conclusion cannot be made for copper and nickel/cobalt from these numbers alone, however, these numbers are compared in later sections of the report with the costs of alternative recovery methods.

4.2. Ion Exchange as the Primary Recovery Method

Ion exchange is well suited to recover metals from solution at low concentrations. Depending on the solution chemistry, metals can either be selectively adsorbed from solution onto several resins, or alternatively selectively eluted if collectively adsorbed onto a single resin. In either case, the product from elution is a purified and concentrated solution, and therefore additional recovery steps are required to transform the metals in solution into marketable products.

Processes to produce marketable products that have been proven over time and that find economic application in commercial scale operations include electrowinning (for higher concentrations) and sulphide precipitation (for low concentrations). Precipitation as the oxide or hydroxide generally leads to the generation of an intermediate product – not final marketable product - such as nickel/cobalt hydroxide, sometimes referred to as MHP, short for mixed hydroxide precipitate. Copper oxide is not regarded as a suitable marketable end product from hydrometallurgical industries.

Figure 2 above shows the permutations of unit operations that can be used to produce marketable products. This information on processing routes is summarised in Table 5. As copper is the main pay metal of this study, the selection of a cost effective ion exchange process for copper essentially narrows the selection of unit operations for the balance of the flowsheet.

In summary, if copper is recovered by ion exchange, then there are generally two proven cost-effective unit operations for the recovery of marketable products from the elution solution containing high concentrations of soluble copper, namely electrowinning and sulphide precipitation. Likewise, for primary recovery of other pay metals from the solution emanating from copper ion exchange the most cost-effective choice is normally another ion exchange step. Similar to copper, there are two proven cost-effective unit operations for the recovery of marketable products from the elution solution containing high concentrations of soluble zinc, namely electrowinning and sulphide precipitation.

Nickel and cobalt are eluted from the zinc resin after the zinc elution. For the recovery of nickel/cobalt from relatively pure high concentration solutions, there are generally four commercially proven recovery steps, i.e. direct electrowinning, sulphiding, carbonation and hydroxide precipitation.

Table 5 : Processing routes for zinc, nickel and cobalt when the primary copper recovery is via ion exchange.

Primary recovery unit operation	Element	Secondary recovery unit operation	Product
IX	Copper	EW	Cu cathodes
		S	Cu sulphide
IX	Zinc	EW	Zn cathodes
		S	Zn sulphide
	Nickel/cobalt	EW	Ni/Co cathodes
		S	(NiCo) sulphide
		Carbonation	(NiCo) carbonate
		Hydroxide precipitation	Mixed nickel cobalt hydroxide precipitate

4.2.1. Operating Costs if Primary Copper Recovery is by Ion Exchange

The relative operating costs for the primary unit operations of ion exchange followed by the unit operations listed above are given in Table 6. In this specific case the products are marketable products. Iron, rhenium, molybdenum, arsenic and vanadium are not recovered as individual products, instead they pass through the ion exchange resin and report to the unrecovered product stream.

Conceivably, another set of ion exchange columns could be added after the nickel/cobalt adsorption step for recovery of additional elements. The operating costs of this additional ion exchange unit operation, followed by the recovery of rhenium from the resin, and transforming the rhenium into a saleable product far outweighs the revenue from it, and therefore it is not even included in this analysis.

Table 6 : Operating costs (annual and unit) of unit operations to produce copper, zinc and nickel/cobalt products when primary recovery of copper is by ion exchange.

Element	Secondary recovery unit operation	Product	Annual Cost € millions per year	Unit Cost € per ton metal
Copper	EW	Cu cathodes	11	613
	Sulphide precip.	Cu sulphide	36	1 997
Zinc	EW	Zn cathodes	1.2	5 771
	Sulphide precip.	Zn sulphide	2.1	10 484
Nickel/cobalt	EW	Ni/Co cathodes	-	N/A[9]
	Sulphide precip.	(NiCo) sulphide	0.7	19 343
	Carbonation	(NiCo) carbonate	-	N/A[10]
	Hydroxide precipitation	Mixed nickel cobalt hydroxide precipitate	>0.8	>20 000

For copper, not unexpectedly, it is seen that copper production by ion exchange and electrowinning has competitive operating costs relative to the unit price of LME copper, and therefore these unit operations are prime candidates for incorporation into a flowsheet for a commercial scale BIOMOre operation. These unit operations have been selected by many previous and current copper operations, and this is primarily due to the cost-effectiveness of these for copper recovery. Except for a few commercial operations in Africa that use copper cementation, all other large scale copper hydrometallurgical producers use electrowinning.

Second in the ranking by operating costs is copper recovery by ion exchange and sulphide recovery. The costs are however not competitive with the selling price of copper. This is due to the large amount of sulphide precipitation agent (typically H_2S) that is required, which is normally not lucrative for large quantities of copper.

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9) The nickel elution solution, though pure, is only about 1 g/L concentration in this case, which is not concentrated enough for electrowinning, and therefore electrowinning is not a real option for this BIOMOre ore.

10) The nickel elution solution is not concentrated enough in this case to warrant the construction of a carbonate precipitation circuit followed by a calciner furnace, a reduction furnace and a sintering furnace, and therefore carbonation is not a real option for this BIOMOre ore.

Table 6 shows that the recovery of zinc by ion exchange and by whatever secondary recovery method is not lucrative. This is mostly due to the small amounts of zinc that are available in this specific ore, and no recovery method is cost-effective enough to treat such large volumetric flows contain very little zinc in solution. (Production of zinc may be only a few hundred tons per year.)

Table 6 furthermore shows that nickel and cobalt cannot be recovered economically from this ore following the recovery of copper by ion exchange. Though technically there are several unit operations to recover nickel and cobalt after primary recovery by ion exchange, the quantities of these elements are so small that spending significant amounts of capital on equipment, for example an electrowinning circuit, cannot be justified. Similarly, the amount of labour needed to dedicate to the production of such small quantities is hardly ever cost-effective.

4.3. Solvent Extraction as the Primary Recovery Method

Several combinations of unit operations are technically available for recovery of elements when using solvent extraction as the primary recovery step. Figure 3 above shows the combinations of unit operations following primary recovery of copper by solvent extraction. Zinc is extracted first, followed by the extraction of copper followed by nickel.

Most of the commercial copper operations that have relatively high copper PLS concentrations (higher than 2.5 g/L) use solvent extraction, and therefore it is expected *a priori* that solvent extraction will be cost-competitive for the BIOMOre project too.

4.3.1. Operating Costs if Primary Copper Recovery is by Solvent Extraction

The relative operating costs for the primary unit operations of solvent extraction followed by the unit operations listed above are given in Table 6. In this specific case the main products are marketable products. Rhenium, molybdenum, arsenic and vanadium are not recovered as individual products, they pass through the solvent extraction steps and report to the unrecovered product stream, or accumulate in one of the reagents, from where it is stripped periodically to avoid poisoning the reagents.

Conceivably, a set of ion exchange columns could be added after the nickel extraction step for recovery of additional elements, like rhenium. The operating costs of this additional ion exchange unit operation, followed by the recovery of rhenium from the resin, and transforming the rhenium into a saleable product far outweighs the revenue from it, and therefore it is not even included in this analysis.

Table 7 : Operating costs (annual and unit) of unit operations to produce copper, zinc and nickel/cobalt products when primary recovery of copper is by solvent extraction.

Element	Secondary recovery unit operation	Product	Annual Cost € millions per year	Unit Cost € per ton metal
Zinc	EW	Zn cathodes	~4	>20 000
	Sulphide precip.	Zn sulphide powder	~5	>24 000
Copper	EW	Cu cathodes	11	609
Iron	Oxidation	Iron(III) solution for re-use	1.8	>1 000
	Precipitation	Oxide / hydroxide / jarosite	>1.8	N/A[11]
Nickel	EW	Ni/Co cathodes	-	N/A[12]
	Sulphide precip.	(NiCo) sulphide	1.1	>28 000
		(NiCo) carbonate	-	N/A
	Hydroxide precipitation	Mixed nickel cobalt hydroxide precipitate	0.8	>20 000

11) The product from this process is a low quality precipitate without commercial value.

12) The nickel strip solution is not concentrated enough in this case to warrant the construction of a carbonate precipitation circuit followed by a calciner furnace, a reduction furnace and a sintering furnace for a production of less than 50 tons per year, and therefore carbonation is not a real option for this BIOMOre ore,

For copper, and expectedly too, it is seen that copper production by solvent extraction and electrowinning has competitive operating costs relative to the unit price of LME copper, and therefore these unit operations are certain candidates for incorporation into a flowsheet for a commercial scale BIOMOre operation. The standard unit operations for solutions with relatively high copper concentrations, such as the PLS of almost all heap leach operations, are SX / EW.

It is seen from the table that the unit cost of zinc production is prohibitively expensive, irrespective of secondary recovery unit operation. This is primarily due to the low zinc production.

Iron can be produced as either an iron(III) sulphate solution or as a precipitate. Neither of these is cost effective in this flowsheet where solvent extraction is the primary recovery method.

Nickel can also not be produced cost-effectively from these solutions when solvent extraction is the primary recovery step. Again, the nickel production is so low that any incremental capital investment to produce nickel, zinc or iron can never be recovered from profits from these elements.

4.4. Cementation as the Primary Recovery Method

Recapping the description of unit operations for the recovery of copper by cementation in section 2.5.4, copper briquettes can be produced from the PLS by cementation with zinc. Copper precipitates and zinc solubilises in the process. Zinc is then recovered using SX, IX or EW, depending on the purity.

Table 8 : Operating costs (annual and unit) of unit operations to produce copper and zinc products when primary recovery of copper is by cementation.

Element	Secondary recovery unit operation	Product	Annual Cost € millions per year	Unit Cost € per ton metal
Copper	Redissolution and briquetting	Cu sponge briquettes	51	2 800
Zinc	Sulphide precipitation	Zinc sulphide powder	52	2 231

It is seen from the table that copper production of cementation with zinc powder is below the selling price of copper of nominally €4 800/t (which was current at the time of assembling the data). It is not clear whether this process is cost-competitive enough to allow a commercial operation to be profitable. On the other hand, when

the operating cost of production of just the unit operations to produce a product alone is more than the selling price of the product, then it can be concluded with certainty that the unit operations cannot be selected for inclusion into any commercial flowsheet. If it was to be included then there is no margin to pay for the operating costs of the rest of the operation, such as mining, bioleaching, or any of the other direct operating cost components.

It is also seen from the table that the operating cost to produce zinc is also above the selling price of zinc, despite the large production of zinc. The reason for this is that a stoichiometric amount of zinc is required to be introduced into the circuit to precipitate all the copper. Without copper cementation the zinc production is in the order of 200 tons per year, and with copper cementation the zinc production is about 22 000 tons per year. Despite this high production, the unit operating cost of zinc production is still more than the selling price of zinc (€1 600/t), thus leaving no margin to offset any other operating costs.

5. Comparative Capital Costs of Unit Operations

The total installed equipment capital costs for the unit operations, as calculated by the methodology described in section 2.2, are given in Table 9 below. The right hand column shows the capital intensity of the incremental project cost, an indicator of the costs involved in equipment payback.

Table 9 : Capital cost of the unit operations for the recovery of metal or intermediate products.

Process	Capital Cost € Millions	Capital Intensity[13] € per ton metal
Sequential Sulphide Precipitation		
Copper sulphide precipitation	9.3	203
Zinc sulphide precipitation	5.1	10 035
Nickel/cobalt sulphide precipitation	3.2	33 525
Recovery by Ion Exchange		
Copper cathodes by EW	19.8	168
Zinc cathodes	3.3	6 612
Zinc sulphide	7.6	15 005
Nickel/cobalt sulphide	5.7	59 900
Mixed nickel cobalt hydroxide precipitate	4.3	46 200

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13) The capital intensity is calculated by dividing the incremental capital cost by the life-of-asset production, considered here as 10 years.

Process	Capital Cost € Millions	Capital Intensity[13] € per ton metal
Recovery by Solvent Extraction		
Zinc cathodes	4.5	8 984
Zinc sulphide	8.8	17 378
Copper cathodes by EW	20.3	173
Iron(III) solution for re-use in bioleach	6.9	1 505
Iron hematite precipitate	12.2	2 645
Nickel cathodes	13.5	143 000
Nickel/cobalt sulphide	15.1	160 000
Nickel/cobalt carbonation	17.3	183 000
Recovery by Cementation		
Copper briquettes	13.8	300
Zinc sulphide powder	5.1	10 035
Rhenium from IX, Evaporation and Recrystallization		
Rhenium metal	17.5	15 600 per kilogram

The capital cost of the unit operations, by itself, is hard to put into perspective, especially since the capital cost for the balance of a commercial BIOMOre operation is not provided, nor relevant. However, the capital intensity allows for an easy comparison of the capital cost. The capital intensity is calculated from dividing the incremental capital cost for the unit operation by the lifetime throughput/production of the particular metal or product. Without getting into a financial treatise here, the

capital intensity can be interpreted as though it was an operating cost; it can also be understood as an indicator for the cost of repayment the capital investment.

In Table 9 it is seen that the numbers for all unit operations for copper production are a small fraction of the selling price of copper. As such, though it adds to the overall cost, the magnitude of the numbers is not such it would make the process definitely unprofitable.

On the other hand, it is seen that the numbers for zinc, and especially for nickel, are above the selling prices of zinc and nickel. This implies that neither of these metals can be produced economically, irrespective of choice of combinations of unit operations.

For iron, either as a solution of iron(III) sulphate, or as hematite, the capital intensity is several orders of magnitude above the price of iron. As such, iron is not an economic product from a commercial BIOMOre project. The analogy with iron ore is made here, and not with value-added product such as paint-quality pigment because it is not customary in the mining and metals industry to fabricate downstream products. This is rather the domain of specialty chemicals, altogether another industry.

For rhenium, similar to iron, the capital intensity is an order of magnitude above the selling price of the metal. This means that the cost of the capital equipment cannot be recovered from the selling of the product. As such, rhenium is not an economic product from a commercial BIOMOre project on this particular Kupferschiefer ore. Other ores may have different concentrations of metals to start with, and may therefore have different conclusions about the cost-effectiveness of recovery of some of the elements.

6. Costs Summary

For a potential commercial scale in-situ ferric leach operation with a copper production rate of about 20 000 tonnes per year from an ore with composition given in Table 2, and mass balance parameters and assumptions as per section 2.1.3, the results of the operating cost and capital cost calculations are summarised in Table 10 below.

Table 10 : Summary table showing the viability of the unit operation combinations for a commercial scale BIOMOre project

Process	Product	Revenue € per ton product	Operating Cost € per ton product	Capital intensity € per ton product	Economical
Sequential Sulphide Precipitation					
Copper sulphide precipitation	Copper sulphide	4 000	1 390	203	Yes
Zinc sulphide precipitation	Zinc sulphide	1 360	4 713	10 035	No
Nickel/cobalt sulphide precipitation	Mixed nickel cobalt sulphide	8 500	4 294	33 525	No
Recovery by Ion Exchange					
Copper by IX/EW	Copper cathodes	4 800	613	168	Yes
Copper by IX and sulphide precipitation	Copper sulphide	4 000	1 997	203	Yes
Zinc by IX/EW	Zinc cathodes	1 600	5 771	6 612	No
Zinc by IX and sulphide precipitation	Zinc sulphide	1 360	10 484	15 005	No

Process	Product	Revenue € per ton product	Operating Cost € per ton product	Capital intensity € per ton product	Economical
Nickel/cobalt by IX and EW	Nickel cathodes	10 000	N/A	36 392	No
Nickel/cobalt by IX and sulphide precipitation	Mixed nickel cobalt sulphide	8 500	19 343	59 900	No
Nickel/cobalt by IX and carbonation	Sintered nickel briquettes	10 000	N/A	52 772	No
Nickel/cobalt by IX and hydroxide precipitation	Mixed nickel cobalt hydroxide precipitate	8 000	>20 000	46 200	No
Recovery by Solvent Extraction					
Zinc by SX and EW	Zinc cathodes	1 600	>20 000	8 984	No
Zinc by SX and sulphide precipitation	Zinc sulphide	1 360	>24 000	17 378	No
Copper by SX and EW	Copper cathodes by EW	4 800	609	173	Yes
Iron(III) solution by SX for re-use in bioleach	Iron(III) solution for re-use in bioleach	-	>1 000	1 505	No
Iron hematite precipitate in autoclave	Iron hematite precipitate	-		2 645	No

Process	Product	Revenue € per ton product	Operating Cost € per ton product	Capital intensity € per ton product	Economical
Nickel by SX and EW	Nickel cathodes	10 000	Note[14]	143 000	No
Nickel/cobalt by SX and sulphide precipitation	Nickel/cobalt sulphide	8 500	>28 000	160 000	No
Nickel/cobalt by SX, carbonation, reduction and sintering	Nickel briquettes	10 000	>20 000	183 000	No
Nickel/cobalt by SX and hydroxide precipitation	Mixed nickel/cobalt hydroxide	8 000	>20 000		No
Recovery by Cementation					
Copper by cementation with zinc dust	Copper briquettes	4 460	2 800	300	Probably not
Redissolution of copper cement and sulphide precipitation	Zinc sulphide powder	1 360	2 231	10 035	No
Rhenium from IX					
Rhenium from IX, evaporation and recrystallization	Rhenium metal	2 000 per kilogram		15 600 per kilogram	No

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14) The nickel elution solution, though pure, is only about 1 g/L concentration in this case, which is not concentrated enough for electrowinning, and therefore electrowinning is not a real technical option for this BIOMOre ore.

From the results it is seen that for the recovery of copper all combinations of unit operations, except for cementation, the operating costs and the capital intensity are below the revenue expected from copper. Copper is the main metal of interest. These results are applicable only to this specific Kupferschiefer ore, which has a relatively high copper concentration, and low concentrations of other metals.

This report does not conclude that a BIOMOre project as a whole will be economical under the conditions stated in this report. It does however find the recovery of copper has a very good probability of being able to provide revenue to cover the other costs of an entire operation.

The other metals, zinc, nickel and cobalt, iron and rhenium cannot be recovered economically under these conditions from an ore with this composition as all of these have incremental operating costs or capital intensity higher than any possible revenue that could be generated by their recovery. This likely stems from the relatively low concentrations of metals in the ore.
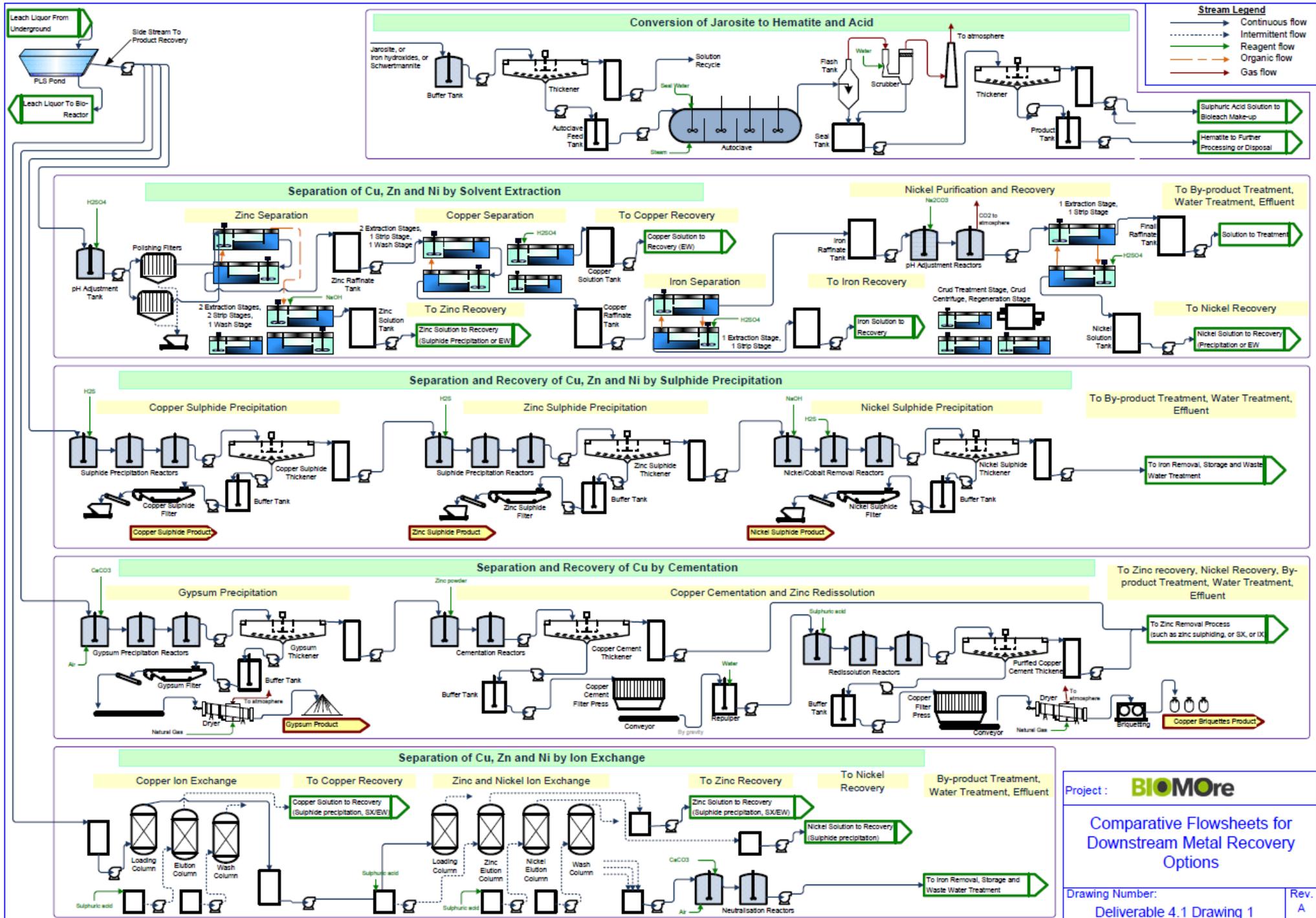
Annex A – Flowsheets-on-a-page

Stream Legend

→	Continuous flow
┄→	Intermittent flow
→	Reagent flow
┄→	Organic flow
→	Gas flow

Leach Liquor From Underground

Side Stream To Product Recovery

PLS Pond

Leach Liquor To Bio-Reactor

Conversion of Jarosite to Hematite and Acid

Jarosite, or Iron hydroxides, or Schwertmannite

Buffer Tank

Thickener

Solution Recycle

Seal Water

Autoclave Feed Tank

Steam

Autoclave

Flash Tank

Water

Scrubber

To atmosphere

Seal Tank

Thickener

Product Tank

Sulphuric Acid Solution to Bioleach Make-up

Hematite to Further Processing or Disposal

Separation of Cu, Zn and Ni by Solvent Extraction

H2SO4

pH Adjustment Tank

Polishing Filters

Zinc Separation
2 Extraction Stages, 1 Strip Stage, 1 Wash Stage

Zinc Raffinate Tank

2 Extraction Stages, 2 Strip Stages, 1 Wash Stage

NaOH

Zinc Solution Tank

To Zinc Recovery

Zinc Solution to Recovery (Sulphide Precipitation or EW)

Copper Separation
H2SO4

Copper Solution Tank

To Copper Recovery

Copper Solution to Recovery (EW)

Copper Raffinate Tank

Iron Separation
H2SO4

1 Extraction Stage, 1 Strip Stage

To Iron Recovery
Iron Solution to Recovery

Nickel Purification and Recovery
Na2CO3

Iron Raffinate Tank

pH Adjustment Reactors

CO2 to atmosphere

1 Extraction Stage, 1 Strip Stage

H2SO4

Final Raffinate Tank

Solution to Treatment

Crud Treatment Stage, Crud Centrifuge, Regeneration Stage

Nickel Solution Tank

To Nickel Recovery

Nickel Solution to Recovery (Precipitation or EW)

To By-product Treatment, Water Treatment, Effluent

Separation and Recovery of Cu, Zn and Ni by Sulphide Precipitation

Copper Sulphide Precipitation
H2S

Sulphide Precipitation Reactors

Copper Sulphide Thickener

Buffer Tank

Copper Sulphide Filter

Copper Sulphide Product

Zinc Sulphide Precipitation
H2S

Sulphide Precipitation Reactors

Zinc Sulphide Thickener

Buffer Tank

Zinc Sulphide Filter

Zinc Sulphide Product

Nickel Sulphide Precipitation
NaOH
H2S

Nickel/Cobalt Removal Reactors

Nickel Sulphide Thickener

Buffer Tank

Nickel Sulphide Filter

Nickel Sulphide Product

To Iron Removal, Storage and Waste Water Treatment

To By-product Treatment, Water Treatment, Effluent

Separation and Recovery of Cu by Cementation

CaCO3

Gypsum Precipitation
Gypsum Precipitation Reactors

Air

Gypsum Thickener

Buffer Tank

Gypsum Filter

Dryer

Natural Gas

To atmosphere

Gypsum Product

Copper Cementation and Zinc Redissolution
Zinc powder

Cementation Reactors

Copper Cement Thickener

Buffer Tank

Copper Cement Filter Press

Conveyor

Water

Repulper

By gravity

Sulphuric acid

Redissolution Reactors

Purified Copper Cement Thickener

Buffer Tank

Copper Filter Press

Conveyor

Dryer

Natural Gas

To atmosphere

Briquetting

Copper Briquettes Product

To Zinc Removal Process (such as zinc sulphiding, or SX, or IX)

To Zinc recovery, Nickel Recovery, By-product Treatment, Water Treatment, Effluent

Separation of Cu, Zn and Ni by Ion Exchange

Copper Ion Exchange
Loading Column

Elution Column

Wash Column

Sulphuric acid

To Copper Recovery

Copper Solution to Recovery (Sulphide precipitation, SX/EW)

Zinc and Nickel Ion Exchange
Loading Column

Zinc Elution Column

Nickel Elution Column

Wash Column

Sulphuric acid

CaCO3

Air

Neutralisation Reactors

To Zinc Recovery

Zinc Solution to Recovery (Sulphide precipitation, SX/EW)

To Nickel Recovery

Nickel Solution to Recovery (Sulphide precipitation)

To Iron Removal, Storage and Waste Water Treatment

By-product Treatment, Water Treatment, Effluent