ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF UNDERGROUND IN-SITU LEACHING PROCESSES UTILISING DRILL AND BLAST TO ACHIEVE HIGH PERMEABILITY

By

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ABSTRACT

In-Place Recovery (IPR) involves blasting a stope, dissolving the metal-bearing minerals within the stope using an appropriate leach solution, and pumping the pregnant leach solution (PLS) to the surface for further processing. While the IPR concept is applicable to various metals, this study was focused on copper extraction mainly to address the future challenge of accessing lower grade and more complex ore bodies in a sustainable manner. In this work, an economic assessment and an environmental impact assessment were conducted to compare copper extraction via IPR with that of conventional mining methods and extraction routes.

A high level economic assessment was completed for a hypothetical 50,000 tonnes per annum copper operation with a head grade of 1% copper from a deposit 500 m deep. Capital investment and the operating cost of the sublevel open stoping (SLOS) method was compared against IPR with three different blast design methodologies. The results showed that both mining and processing capital costs of an IPR operation are significantly lower than that of SLOS. IPR benefits from lower direct operating cost, despite lower recoveries and a higher number of stopes in operation to equate the production rate of SLOS. Lowered haulage and the reduced amount of development were the main contributing factors to the cash cost saving. A sensitivity analysis was performed to assess the response of net present values (NPV) to copper grade, operating cost, initial capital cost, and copper price. The results showed that SLOS is more sensitive to all four parameters. Hence, for an increase in head grade or copper price SLOS is more profitable, while at lower grades and copper prices IPR is more profitable. While an optimum technology choice can only be made upon detailed consideration of the relevant facts for each specific project, the economic assessment in this work revealed that at low grades of copper an IPR operation is more profitable than conventional SLOS method due to the reduced operational cost and initial capital investment. As the stope configuration in IPR can be aligned with conventional mining methods, there is scope to run a hybrid operation where high-grade ore is mined and processed conventionally, and the low-grade ore is recovered through IPR. This allows the IPR technology to be an addition to an existing operation.

Environmental concerns such as greenhouse gas emissions, energy consumption, water consumption, and land disturbance play a governing role in restricting future operations. The environmental impacts of IPR were compared to conventional underground (UG) and open-pit operations combined with either pyro- or hydro-metallurgical processing. When comparing the CO_2 per tonne of Cu for a range of mining-processing streams, IPR with solvent extraction/electrowinning (SX/EW) is significantly less polluting than a surface mining operation with heap leach pads and SX/EW or an underground operation with concentrators, smelter, and electro refining. Technologies such as IPR allow the targeted extraction of metals from the ground resulting in significantly reduced land disturbance and other environmental impacts. The technology could be a significant contributor in underground operations achieving a net zero target by 2050.

Keywords: underground mining, Copper, In-Place Recovery, Cash Flow analysis, Environmental impact

INTRODUCTION

Population growth, increase in living standards, and transition to green energy through electrification is anticipated to skyrocket the demand for critical minerals. Meeting this growing demand is made more challenging considering that miners are facing more complex and deeper ore bodies at lower grades. Traditional surface mining methods with a large footprint are becoming unviable economically, and unacceptable socially and environmentally, resulting in a transition to underground operations. Yet, increased sustainability, enhanced efficiency, waste reduction, and a strong focus on safety requires the underground mining industry to look at cleaner approaches to meet the growing demand and ESG (Environmental, Social, and Governance) requirements. Both costs and the environmental impacts of conventional mining methods rise noticeably with deepening deposits and lowering ore-grades.

In contrast to conventional mining methods, with in-situ metal extraction operations, the mineral is extracted without moving the rock to the surface. In-situ Leaching (ISL) consists of the underground circulation of a solvent (lixiviant) through an ore deposit with sufficient permeability, dissolution of target metal(s) forming a pregnant leach solution (PLS) and pumping the PLS to the surface. The metal is then recovered from the fluid at a surface processing facility. Limited permeability affects the exposure of the ore minerals to the lixiviant, reducing recovery. While there are several permeability enhancement technologies available that can aid metal recovery from naturally permeable formations, there are no ISL operations in production for low permeability hard rock deposits. A means of leaching hard rock deposits in-place is to access the deposit through conventional underground mine development, blast the ore in a stope, dissolve the metal-bearing minerals within the stope using an appropriate leach solution, and pumping the PLS to the surface for further processing. While the application of this In-Place Recovery (IPR) technology is described in this paper in relation to copper recovery this concept is not limited to copper but extends to other base metals such as nickel and cobalt, and precious metals such as gold.

The type of ore being mined is a deciding factor in how the elemental metal(s) are extracted from the mineralogy. The two common processing routes for extracting base metal from its ore can be described as the pyrometallurgical route and the hydrometallurgical route. The pyrometallurgical process consists of beneficiation (crushing, milling and floatation) and smelting while the hydrometallurgical route involves leaching the metals from the ore followed by solvent extraction or an ion-exchange process. The hydrometallurgical path is often selected for oxidised minerals, whereas primary sulphides cannot be easily dissolved in aqueous solutions and are typically extracted via the pyrometallurgical path. However, miners face penalties when selling concentrates with high levels of impurities to smelters since certain elements (e.g. lead, arsenic and mercury) cause issues, such as occupational health exposure of smelter workers, increased operating cost by necessitating removal processes, increasing disposal cost, and reducing cathode purity. The smelters often blend high impurity concentrates with “clean” concentrates to dilute the level of impurity. However, with the growing level of impurities and shortage of adequate clean concentrates, diluting is becoming more challenging for smelters(1).

The majority of metal produced through hydrometallurgy is via heap leaching, consisting of building head pads with crushed/agglomerated/cured ore, and percolating leach solution through the heap pads by gravity. Heap leaching operations are vulnerable to weather conditions. Daily and seasonal temperature fluctuations, rain, snow, and storms can potentially have detrimental effects on the performance of a heap leaching process. The overall metal recovery depends on the sweep efficiency, as defined as the fraction of metal bearing species contacted by the leach solution, and the metal dissolution governed by the leach kinetics.

Hydrometallurgical treatment has found extensive application for leaching copper from copper oxide and secondary sulphide ores using acid solutions due to its simplicity, relatively high extraction recovery, low capital and operating cost, and ease of operation. Secondary sulphides can suffer from slow dissolution of copper, which can be improved through the work of microorganisms, termed bioleaching. Hydrometallurgical processing reduces the marketing risk associated with high-impurity concentrates(2). On the other hand, leaching copper from primary copper sulphides is at the early stages of development and research. The slow dissolution rate and formation of a passive layer, hindering further recovery, has encouraged mine operations to select pyrometallurgical process for such ore types. Also, leaching typically does not recover any precious metals as by-products from the ore, and high acid consuming gangue minerals can increase the operating cost and detrimentally effect leach performance.

IN-PLACE RECOVERY

The concept of forming an underground 'heap' of broken ore which is leached within the mining operation is not new. Middlin and Meka[3] reported on the successful underground heap leaching at the re-started Mammoth Mine near Gunpowder in Queensland. The operation employed long-hole stoping to blast the sulphide ore, and utilised bioleaching to recover ~5000-6000 tpa of LME Grade 'A' in the first few years of operation. Bioleaching was also applied in a stope leaching trial of a sulphidic ore at Ilba Mine in Romania[4]. The stope was 10 m long, 10 m high and 1 m wide (the thickness of the ore vein), and dipped at 75°. However, the field trial recovery was lower than what was achieved in the laboratory due to only the top portion of the stope leaching as the dip angle caused the lixiviant to flow down the footwall for most of the stope, this also resulted in loss of lixiviant. In 1994 the U.S. Bureau of Mines[5] posted a bulletin on stope leaching in underground mines to reduce surface environmental impacts from underground mining. O'Gorman[6] proposed a large-scale low-cost mining method where a relatively shallow ore body has underground development to access the bottom. The deposit is then drill and blasted from the surface, and the lixiviant irrigated on the surface and the PLS recovered from the underground workings. Broken ore is slowly removed from underground to eliminate channelling and enhance the contact between the ore and the lixiviant (sweep efficiency).

More recently Orellana[7] assessed the feasibility of an IPR operation for two deposits, Tkoi and Quetena, in Chile. Various stope configurations were assessed based on operating cost and operability. Costing of the operations were based on data from two sub-level open stoping operations in Chile. Previous studies for the deposits found them uneconomical for conventional underground mining methods, and an open-pit operation with heap leach would not be sufficiently profitable. Orellana showed that an IPR operation would be more profitable than the proposed open pit mine. Mining3 coined the term In Mine Recovery (IMR) for IPR and conducted a thorough analysis of the potential to utilise IPR in conjunction with a conventional stope mining operation to increase the net present value (NPV) of the operation[8]. A reserve block model was generated for a hypothetical deposit and a mine planning model created and applied to the block model to sequence which stopes should be mined conventionally or using IPR to maximise the NPV. Including IPR in the operation significantly increases the number of stopes mined, due to IPR being more profitable for lower grade stopes, and increases the profitability of the operation. The value of the project was found to be very sensitive to the assumed metal recovery.

A method of creating stopes of broken rock for leaching in an IPR operation based on the remote ore extraction system (ROES)[9] provides a safe means of automating the drill and blast process[10] (Figure 1). ROES is a mechanised variant of the Horidiam mining method, where horizontal rings of blastholes are drilled and blasted from within a raise while retreating vertically upward. Further work demonstrated other methods of blasting ore bodies to provide broken stock for leaching[11].

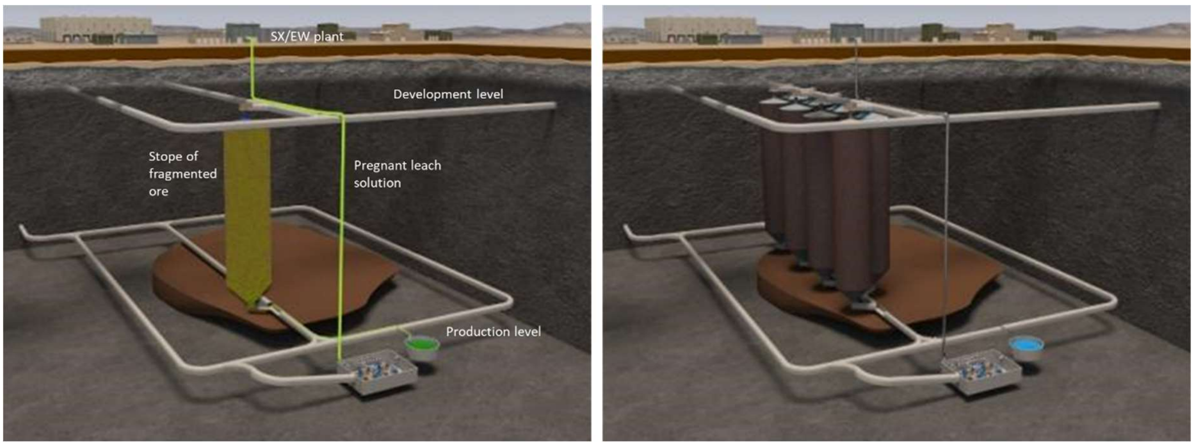

Figure 1. Example of a single stope (left) and array of primary production stopes (right).

Rossien[12] completed an economic study of IPR and determined the NPV for a hypothetical copper deposit, the presentation of the NPV data and sensitivity analysis in the paper was considered very clear and thus the format was utilised by the authors in this paper. A second part of the study assessed the value of IPR, conventional underground, and an expansion of the current open pit, to access ore beyond the current ultimate pit limit for an Australian gold mine. IPR was the only method to return a positive NPV for the deposit, however, the grade distribution and the requirement not to mine up to the existing pit shell made it difficult to maximise the recovery of the higher-grade ore with the IPR stopes.

The above brief history of IPR highlights the care that needs to be taken when conducting trials. The desktop studies show the potential economic benefit of developing IPR operations alongside or instead of conventional mining methods. Despite the lower metal recovery of IPR leaching operations compared to conventional mining with beneficiation and smelting, the lower capital and operation costs of IPR allows for the economic extraction of lower grade ore.

The following study makes a direct economic and environmental comparison of IPR and a conventional underground sub-level open stoping operation for a hypothetical copper deposit. An analysis which has not been undertaken in the previous studies.

CASE STUDY

Sub-level open stoping (SLOS) is a common underground mining method that is utilised in hard rock metal mines. SLOS has the potential to produce stopes full of broken stock, therefore, it is a readily transferable mining method to IPR. As such a case study based on SLOS, with a directly transferrable mine development infrastructure and cost, allows for a directly comparable cost analysis between SLOS and an IPR design utilising the open stoping method. Further there are two large, well-documented, SLOS operations, BHP's Olympic Dam and OZ Minerals' Prominent Hill, both in South Australia, to utilise in developing a case study.

To develop the alternative mining methods, a common target of 50,000 tonnes per annum of copper concentrate/metal was selected with an initial head grade of 1% copper. All methods utilise a decline as the access to the deposit with all the required ore trucked to the surface. For a decline angle of 7° (1 in 8), to achieve a depth of 500 m, will require approximately 4 km of decline.

For the SLOS method (Figure 2), assuming 90% recovery in creating the concentrate and 5% dilution during excavation, requires 5.8 million tonnes of ore mined per annum to achieve 50,000 t Cu per annum. The operation will use 60 tonne capacity dump trucks at a rate of approximately 11 trucks per hour to move the required ore.

Stopes are 100 m high and 100,000 m^3 in volume, with a nominal width and depth of 32 m, and assuming an ore density of 3 g/cc, containing 300,000 tonnes. Therefore, to achieve the production target 19 stopes will have to be recovered per annum. Rather than go to the detail of calculating the individual development requirements per stope, a generalised development of 450 m per stope was derived based on the data from Uggalla[13] on the requirements for Olympic Dam.

The stopes have a sublevel spacing of 50 m, therefore up and down blasthole ring designs have a nominal 25 m ring height. A generalised blast design with 115 mm diameter blastholes on a ring pattern of a 3 m burden and 4 m toe spacing, charged with bulk emulsion, and fired with electronic initiation was used for drill and blast costings.

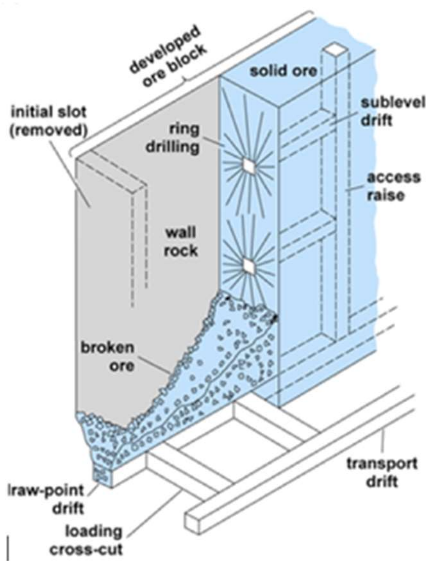

Figure 2. Example configuration of a SLOS operation, after[14]

For IPR, assuming an initial recovery of 50% from the leaching operation, requires 10,000,000 tonnes of ore to be in production per annum to achieve the target copper metal production of 50,000 tonnes, using the same initial head grade. It has been assumed that 20% of the ore in the stopes will be trucked to the surface, and processed in surface leach pads, to ensure sufficient void to effectively blast the remaining material in the stope.

The stope height is kept at 100 m, however, due to the required tonnes of ore to leach, the stope volume was increased to 200,000 m^3, with a nominal width and depth of 45 m, and 600,000 tonnes of ore in each stope.

Three blast design methodologies are proposed to achieve the desired fragmentation and swell to generate an effective leach environment within the stopes (Figure 3). The first method uses conventional long-hole stoping (LHS), whereby rings of blastholes are vertically orientated, similar to SLOS, however, without the sublevel and using longer blastholes, with a ring height of 50 m compared to 25 m for SLOS. As with SLOS a vertical slot will be blasted and excavated, to create the 20% void, and the rings fired into the slot. The designs can be fired with conventional electronic initiation systems, or potentially more effective designs could be fired in part with wireless initiation. The second method is an adaptation of the ROES concept where a large diameter raise is excavated up the middle of the stope, a platform is lowered into the raise, with remote drilling of the horizontal rings of holes[10]. An automated charging system loads all the holes with wireless primers and bulk explosive prior to blasting. The rings are blasted downwards in stages, with the drawbell being fired first. After each blast a small amount of material is extracted at the production level to provide relief (void) for the next stage to blast into. In the third method, again a raise bore is excavated between levels, however, with a smaller diameter than is required with the ROES technique as it is only providing void for blasting, not access to the stope[11]. Then a pattern of vertical large diameter holes (LDH), up to 229 mm in diameter, are drilled with a mobile raise bore rig around the raise. All the blastholes are loaded with wireless primers in multiple decks of bulk explosive separated by inert stemming prior to blasting. Each horizon of explosive charges is a stage which are fired sequentially from the bottom up.

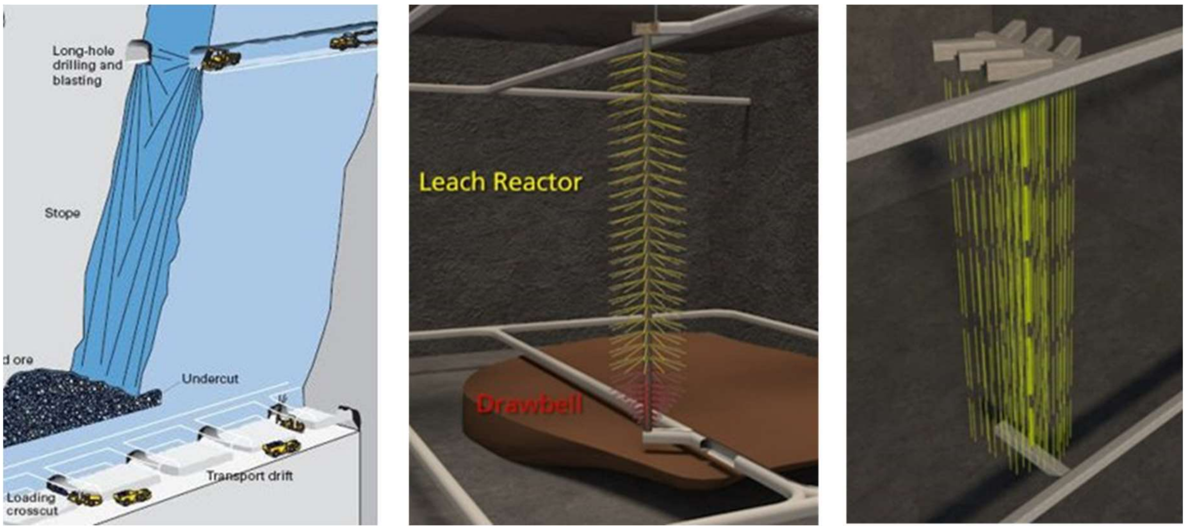

Figure 3. Design options for IPR, long-hole stoping (left, after[15]), remote ore extraction system (middle), and large diameter holes (right).

A summary of the blast design parameters for the four designs (Table 1) highlights the increase in powder factor for IPR compared to SLOS, as the IPR designs will require finer fragmentation for effective leaching compared to typical stope blasts. Correlating blast fragmentation particle size distribution to leach recovery and rate is beyond the scope of this study, therefore, the powder factors selected for IPR were based on changes in pattern that can be easily implemented, while maintaining the hole diameter in the LHS and ROES designs compared to SLOS.

Table 1. Summary of blast design parameters.

Design	SLOS	IPR		
		LHS	ROES	LDH
Stope size (t)	300,000	600,000	600,000	600,000
Burden (m)	3.0	2.0	2.0	4.5
Spacing (m)	4.0	4.0	3.0	4.5
Hole Diameter (mm)	115	115	115	229
Powder Factor (kg/t)	0.34	0.72	0.65	0.55
Drill Factor (t/m)	22.0	10.6	12.6	75.1

Economic Assessment

The operating cost (i.e., cash cost) consists of direct operating cost, sustaining capital cost, and indirect operating cost. Direct operating cash cost consists of drilling, blasting, backfill, load and haul, ventilation, and dewatering. It is apparent that the direct operating cost is a function of mining method and drill and blast design. Sustaining capex refers to the on-going cost of development in the underground area. Indirect operating cost including maintenance, and general and administration (G&A) have been calculated as a percentage of direct operating cost. The total operating cost of the mine is then added to the operating cost of the mineral processing plant.

Insurance, working capital, and deferred capital have not been included in this analysis.

Capital Cost

A significant portion of the initial mining capital cost is the same between SLOS and the IPR mine designs. For example, the ventilation shafts, dewatering station, and surface facilities are taken as the same (Table 2). Due to the significantly less ore being trucked to the surface in the IPR designs the size of the decline is taken as 5.5 m by 5.8 m compared to SLOS with a 6.0 m by 6.5 m decline, with costs of 7,000 and 9,000 $/m, respectively. The IPR mobile equipment costs were reduced by 50% of the SLOS costs considering the trade-off between the reduced ore movement and increased drilling requirement. Less ore movement to the surface results in reduced capacity and truck fleet size. However, extra capex has been allocated to consider increased production drill requirements to blast more ore at higher powder factors compared to SLOS. The engineering & management, and contingency costs were taken as percentages of the sum of the previously derived costs. Overall, the capex for IPR is approximately 25% less than that for SLOS.

To compare the capital investment requirement for hydro- and pyro-metallurgy operations side by side data from Centinela Chilean copper operations, that have both processing plants, was obtained from Wood McKenize[16] asset reports. This effectively normalises against variations in design, sourcing, and fabrication. The pyrometallurgy plants cost more than double the hydro plants and the data was extrapolated using the factored cost estimate to derive the data in Table 2.

Table 2. Summary of capital costs for SLOS vs. IPR.

Design	SLOS	IPR
Mining ($M):		
Decline	36.6	28.5
Three Ventilation Shafts, each	7.0	7.0
Dewatering Station	15.0	15.0
Surface Facilities	20.0	20.0
Mobile Equipment	60.0	30.0
Engineering & Management	26.0	19.5
Contingency	30.5	22.9
Mining Total	209.1	156.9
Processing Total ($M):		
Beneficiation Circuit	824.0	-
Small-scale Heap Pad	-	18.7
SX/EW	-	341.0
Lixiviant Pumping	-	5.0
Transport	15.0	10.0
Processing Total	839.0	374.7
Mining & Processing Total ($M)	1,0448.1	531.6

Operating Cost

The metres of development ($5,000/m) and ventilation requirements per stope for the SLOS was taken from Uggalla[13]. Despite the larger stope sizes in IPR compared to SLOS, the amount of development tunnels required to access the IPR stopes is considerably less due to the lack of any sub-level development required and an overall reduction in ancillary development. Therefore, the IPR development requirement was reduced by 70% (of SLOS) for the LHS and ROES designs, while for the LDH more development will be required at the production level to drill the vertical blastholes (Figure 3) and development was taken as 80% of SLOS. The ventilation requirements for IPR were reduced from the SLOS value by the same percentages as used for the development requirements. The main fan energy requirements were derived from Morla *et al*.[17].

It is common to present mining costs as $/t of ore mined, however, as the mining costs and percentage recovery of metal from the ore are very different for the two mining methods, a more meaning full comparison is $/t copper. Drilling costs were derived from the production drill metres required for the blast designs (Table 1) multiplied by the relevant drilling costs, taken as $40/m for a 115 mm diameter hole, and $200/m for the 229 mm diameter holes in the IPR-LDH design. Blasting costs were derived from the list price of detonators, primers and bulk explosives for the relevant blast designs, and a nominal charging labour cost of $10/m. Backfill costs were determined assuming 60% of the void in the stope is filled with cemented rock fill at $8/t. Haulage costs used data from Orellana[7] at $0.8/t-km, assuming a round trip of 10 km. The ventilation and dewatering costs used a grid power cost of $0.14/kWh. The auxiliary mine ventilation costs were taken as 10% of the main ventilation costs. Maintenance was taken as 28%, G&A 19%, and indirect costs 20% of the combined sustaining capital and direct operational cost. Maintenance includes upkeep of all fixed and mobile plant. G&A includes water treatment, environmental and camp costs. Indirect costs include, auxiliary electrical, process water, underground upkeep, and reconditioning.

The derived total mining operating costs (Table 3) show that all the IPR drill and blast techniques assessed have a lower cost than SLOS. Within the IPR methods the LDH has the potential to have the lowest cost, however, the technique is also the most novel. The ROES method has the highest cost of the IPR techniques, this is for the most part, due to the high cost of developing the large raise bore in the stope.

Table 3. Mining operating costs.

Design	SLOS	IPR		
		LHS	ROES	LDH
Stope size (t)	300,000	600,000	600,000	600,000
Stopes mined per annum	19	17	17	17
Development per stope (m)	450	315	315	360
Water ingress (m^3/day)	5,000	6,000	6,000	6,000
Dewatering energy (kWh/day)	14,340	17,210	17,210	17,210
Ventilation airflow (m^3/s)	2,683	1,610	1,610	1,610
Vent. power – main (kW)	6,707	4,024	4,024	4,024
Vent. energy – main (MWh/annum)	58,750	35,250	35,250	35,250
Sus. CAPEX – development ($/t Cu)	833	525	525	600
OPEX – direct ($/t Cu)				
Drilling	202	751	1,039	799
Blasting	152	507	533	205
Backfill	533	192	192	192
Load	556	200	200	200
Haul	905	326	326	326
Ventilation – main	157	99	99	99
Ventilation – aux.	16	10	10	10
Dewatering	14	18	18	18
Sub-total	2,534	2,102	2,416	1,848
OPEX – indirect ($/t Cu)				
Maintenance	941	734	822	684
G&A	644	502	562	468
Indirect costs	674	525	588	490
Total	5,626	4,389	4,913	4,090

For mineral processing operating costs associated with leaching, Table 4 assumed an acid consumption of 3 t/t Cu[1]. The acid price was set at $210/t, equating to $630/t Cu. Ferric ion concentrations were set at 6 g/l, based on Talyor[(18)], requiring Ferric sulphate at a cost of $3.6/t Cu, based on a unit cost of $200/t. PLS concentration was assumed to be 3.5 g/l[(18)]. Based on a head height of 500 m, PLS pumping will require 75.6 MW/day at a cost of $77/t Cu. The final leaching cost included 20% contingency.

The hydrometallurgical SX/EW and G&A costs, and the pyrometallurgy beneficiation (milling and flotation) and G&A costs were derived from the summary data from Chilean operations[(16)]. To express all the costs in terms of $/t Cu, an ore grade of 1% and copper recovery of 90% for SLOS and 50% for IPR were assumed. To compare the total cost of *copper cathode* production, the costs of transporting the concentrate from the plant to the smelter and the cost of smelting have been added to the pyrometallurgy route. Transport cost is a rough estimate only as it highly depends on the distance of the mine to the port and the smelters, and available transport options.

For this example of mineral processing operating costs (Table 4), from run-of-mine to metal cathode, the hydrometallurgy process is nearly 30% less expensive than the beneficiation/pyrometallurgy process. Within IPR mineral processing, the largest cost is in the leaching, specifically the acid consumption. While in pyrometallurgical processing the largest cost is in milling, specifically the energy consumed in grinding.

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[1] Acid consumption depends on ore mineralogy, gangue composition, ferric ion solubility, jarosite precipitation, irrigation rate, permeability, required PLS acidity, and microorganism activity (in case of bioleaching).

Table 4. Mineral processing operating costs.

Design	SLOS	IPR
Hydrometallurgy ($/t Cu)		
Leaching		857
SX/EW		747
G&A		363
Hydrometallurgy Total		1,966
Pyrometallurgy		
Beneficiation	1,267	
G&A	232	
Beneficiation total	1,499	
Transport	320	
Smelting	900	
Pyrometallurgy Total	2,719	

The total operating costs (Table 5) combine the total mining operating costs (Table 3) and the total mineral processing operating costs (Table 4). The IPR-LHS method has an operating cost that is over 20% less than SLOS. The operational cost breakdown is consistent with the cost distribution provided by Rossien[12].

Table 5. Total operating costs.

Design	SLOS	IPR		
		LHS	ROES	LDH
OPEX – Total ($/t Cu)	8,345	6,355	6,880	6,056

Cash flow analysis

A first-pass economical model was constructed for the case study, enabling NPV and input sensitivity analysis to be performed for the two mining methods. The model assumes a 15-year life-of-mine, with three years of mine closure costs at $10M per annum, costed as sustaining capital costs, after production has ceased. The tax rate was set at 27.5%, with a discount rate of 7.5% and royalties at 2%. The copper price is set at $12,000/t.

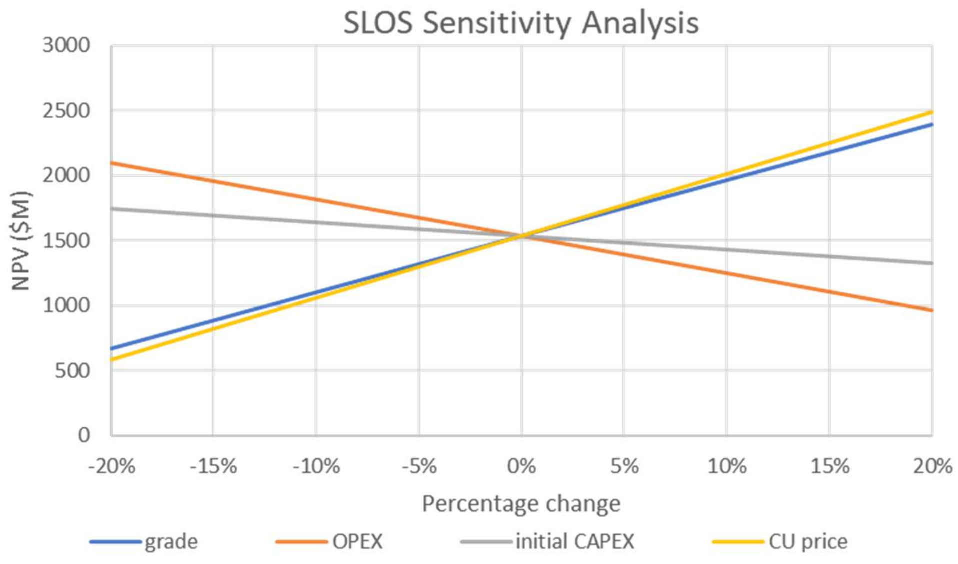
The SLOS mine is assumed to ramp up to full production over three years, while the IPR-LHS is set to take four years to reach full production (Figure 4). While the two mining methods were designed to produce the same amount of copper per year in full production, the SLOS has higher revenue due to the assumed gold and silver credits from the smelter at $1,700/t Cu, also the IPR-LHS has reduced revenue due to solution losses within the stopes, assumed to be 5%.

The SLOS operation has a final NPV of $415M and a pay-out time of nine years, compared to the IPR-LHS operation with an NPV of $689M and a pay-out time of six years.

Figure 4. Comparison of cash flow curves for SLOS and IPR-LHS.

With a basic economic model constructed it is possible to perform a sensitivity analysis on a range of input parameters to determine their relative impact on the profitability of the operation. To make a clear comparison of the sensitivity analysis between the two mining methods it was considered pertinent to adjust the head grade of the deposit until the NPV's matched. This was achieved at a grade of 1.35% Cu for an NPV of $1,540M, below this grade IPR is more profitable, and above it SLOS is. The grade to match NPV's is specific to this example case study, however, the trend highlights IPR as more profitable at lower grades, due to the lower recovery and mining costs compared to SLOS. Comparing the sensitivity analysis (Figure 5), the higher capital and operating costs of the SLOS naturally are more sensitive to changes in those costs compared to IPR. SLOS is also more sensitive to grade and copper price than IPR, hence SLOS is more profitable in higher grade deposits. While IPR is more suitable to lower grade deposits with less selective stope development. For both analysis the profitability is most sensitive to the copper price, the one parameter that the operation has no control over. The operations are marginally less sensitive to grade than the copper price, hence the importance of an accurate block model and grade control program. For IPR the sensitivity for recovery is the same as grade, the recovery line in the graph has been offset a little from the grade line to improve visibility.

While in this paper, a greenfield IPR project was studied economically, the application of IPR in brownfield operations also has massive potential by increasing the total recovery and extending the mine-life, especially for less attractive mineralisation where conventional mining is uneconomic.



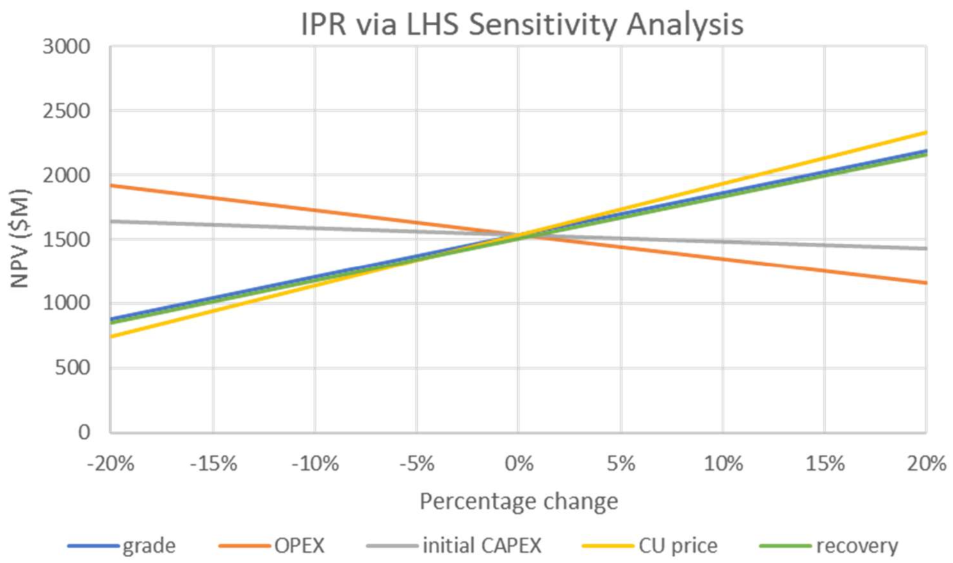


Figure 5. Comparison of NPV sensitivity analysis.

Environmental Impact Assessment

Compared with a conventional copper extraction operation, metal extraction via IPR requires minimal rock haulage and eliminates the need for costly beneficiation circuits. Some of the significant environmental advantages of IPR compared to conventional mining are as below:

- Increased safety due to reduced exposure to hazardous areas.
- Reduced energy consumption and greenhouse gas (GHG) emission due to reduction in material extraction and elimination of underground crushing and conveyance system, and elimination of the comminution circuit.
- No tailing generation
- Reduced land disturbance with much smaller surface footprint
- Reduced backfill
- Reduced dust emissions
- Lower noise level

From an environmental point of view, products and processes can be quantitatively compared through a Life Cycle Assessment (LCA) in terms of various impacts such as global warming and water use. Global warming impact is a function of both the energy consumption, and the source of energy. It is apparent the application of diesel generators and diesel-operating equipment contribute to much higher GHG emissions, and therefore, higher global warming impacts, compared to other power sources. Water use (or water footprint) is another crucial environmental indicator based on quantity of water used and its direct and indirect associated impacts.

GHG Emissions

An open-pit mining operation with Leach/SX/EW emits approximately 2.84 tonne of CO_2 per tonne of Cu, while an underground mining operation with Concentrator/Smelter/ER results in 3.3 tonne of CO_2 per tonne of Cu. It is worth noting that the values presented here are based on an average of all copper operations in Chile in 2018 which is consistent with the average literature data(19).

For an IPR copper operation, the GHG emissions of the underground operation is less intense than a conventional underground mine as much less material is extracted and transferred to the surface. With regards to leaching, the GHG emissions associated with building a heap pad including primary crushing, agglomerating, and conveying or haulage of rock will be reduced by at least 80%. However, indirect GHG emissions from pumping the lixiviant needs to be considered. The overall GHG emissions for IPR has been derived at 1.6 ± 0.4 tonne of CO_2 per tonne of Cu, which is up to 50% lower than the emissions from open-pit mining/heap leaching or underground mining/smelting operations.

Water consumption

In a beneficiation circuit, flotation is carried out at 25 to 40% solids, consuming between 1.5 to 3 m^3/ton of ore(20). In some operations, water is used to transport the concentrate as a slurry. In this case, the water used for pumping the concentrate represents 4-6% of all the water consumed in the concentrating plant(21). After delivering the slurry near the port, the water is separated through thickening and filtration prior to transporting the dry concentrate (at 10% moisture) to smelters. Depending on the distance and elevation difference, the recovered water may or may not be recirculated to the process. Nonetheless, a large portion of water used in flotation is carried over to tailings. Water recovered during thickening of the tailings and from tailing dams can be recirculated to the flotation. Yet, up to 15% of the water in tailings can be lost due to evaporation(20).

The concentrate is then dried to below 0.2% moisture content prior to smelting. At the smelters, water is used in oxygen production, cooling the produced gas during the fusion, and in the sulphuric acid plant. Depending on the closeness to the sea for sourcing cooling water, the water consumption varies. Average water requirement for smelting in Chile is around 3.6 m^3/tms[2] of cast concentrate(21).

In the hydrometallurgical process, water is used in agglomerating, heap leaching, and solvent extraction. Before building the heap pads, the moisture content of the crushed ore is increased to 10% during agglomeration. Depending on the heap pad construction method and weather conditions, significant water can be lost through evaporation off the heap pads and the PLS/LS ponds. In solvent extraction, the organic solution is frequently rinsed resulting in a high volume of water usage. Compared with a heap leaching process, it is expected that IPR will have reduced water consumption owing to elimination of crushing and agglomeration, and significantly less evaporation in an underground environment.

Overall, while the total unit consumption of freshwater in a beneficiation circuit range between 0.3 to 2.1 m^3/tonne of ore, in 2006, water consumption at a typical Chilean beneficiation plant was reported as approximately 0.8 m^3/ton ore enabled via significant water recovery and modern sealed tailings. This value can be further optimized to achieve 0.36 m^3/ton in the best operations. On the other hand, hydrometallurgical plants consume around 0.08 to 0.25 m^3/ton of ore (Santoro, Estay et al. 2021). In 2006, Chilean operations reported to consume only 0.13 m^3/ton through improved solution recirculation and minimising evaporation(21).

An IPR operation should consume less water compared with a heap leaching process given that evaporation will be significantly reduced. However, while the water consumption in terms of cubic

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[2] tms and TMS are two units of mass used interchangeably in reports published by Cochilco for processed ore and copper concentrate. On the other hand, FTM and TMF (ton of fine Cu contained material) are often used to express the mass of copper cathode. However, it is not clear to the authors whether t or T stand for metric tonne or short Ton.

metres per tonne of ore will be lower, in expressing the water usage per tonne of Cu the lower recovery in an IPR operation must be considered.

It is anticipated that water consumption of a copper IPR operation combined with SX/EW processing will be limited to 0.2 m^3/ton of ore. It is worth adding that the water consumptions presented above for pyro- and hydro- metallurgical routes did not include water use for mining. However, the estimated value for IPR/SX/EW consists of both mining and metal production.

From an ESG point of view, copper extraction via IPR has much less detrimental effects on the environment; hence, speculated to facilitate the grant of licence to operate. Additionally, the reduction in capex and opex lowers the cut-off grade allowing profitable extraction of metals such as copper and nickel from deposits which are uneconomic to mine conventionally. This assists with meeting the increased demand for copper and nickel, especially considering the role these commodities play in the transition to low carbon emissions.

FIELD APPLIACTION OF IPR

There are several variables that will influence the recovery rate of metal from a stope that need to be addressed prior to a trial within a specific deposit. As with surface leaching operations a significant program of hydrometallurgy test work from bottle roll to column tests will be required to characterise the ore over a range of lixiviant chemistry and leaching conditions. If long-period circulation of the solvent is required to achieve an economic recovery, the effect of side reactions on permeability fluctuation and short circuiting must be carefully studied over the same period in the laboratory. Blast modelling is also important to determine the fragmentation particle size distribution and heave induced permeability through the stope. And hydrology modelling to determine the fluid flow through the stope for a given modelled permeability, targeting uniform liquid, and gas if required, distribution, and assess the extent of short circuiting (channelling) or fluid entrapment prior to leaching. By combining the blast modelling, fluid flow transport and kinetics (leaching) models, a comprehensive IPR simulation tool can be developed to predict and optimise metal recovery from a stope.

Containing the solution within the stope will be in the forefront of mining operations to prevent potential environmental contamination or loss of leached metal. While the implementation of a barrier can be considered in an ISL operation targeting shallow deposits, many of the available barrier technologies are not suitable for IPR due to the lack of access from the surface. However, it is expected that once a stope within a competent rock mass is fractured, the lixiviant preferably percolates through the broken ore body.

CONCLUSIONS

While the IPR concept is applicable to various metals, this study focused on copper extraction mainly to address the future challenge of accessing lower grade and more complex ore bodies in a sustainable manner. Currently about 80% of copper is produced pyrometallurgically; however, with ongoing developments in leaching technologies and more restrictions on smelting the contaminated concentrates, the portion of copper produced from the hydrometallurgical route is increasing. Advancements in leaching copper from secondary copper sulphides has enabled more penetration of hydrometallurgical processing given its lower capital cost and operating cost requirements. Similarly, enhanced leaching kinetics of primary copper sulphides will broaden the application of IPR in extracting copper from chalcopyrite which is the most abundant copper sulphide mineral.

While an optimum technology choice can only be made upon detailed consideration of the relevant facts for each specific project, the economic assessment in this work revealed that at low grades of copper an IPR operation is more profitable than conventional SLOS method due to the reduced operational cost and initial capital investment.

Nonetheless, economic merits are not sufficient to obtain regulatory approvals for a mining operation. Environmental concerns such as GHG emissions, energy consumption, water consumption, and land disturbance play a governing role in restricting future operations. Operations such as IPR allow the targeted extraction of metals from the ground resulting in significantly reduced land disturbance and other environmental impacts.

Technological innovations in the mining industry are often adopted slowly; however, with increasing attention to ESG and ambitious net zero emission targets, the industry is expected to welcome both incremental and fundamental innovations. On the other hand, to mitigate the risk associated with the high level of uncertainty with fundamental changes, such as adoption of novel mining methods, an appropriate and in-depth pre-feasibility study must be completed. Various experts in the fields of underground mining, copper leaching, blasting, fragmentation modelling, fluid transfer modelling as well as social scientist and consultants must work closely to gain fundamental knowledge and quantify the risk and opportunities. It is also critical to establish and maintain a sustainable and trusted partnership with all stakeholders, especially the local community.

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