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Industrial upscaling feasibility assessment and identification of key performance indicators for an in-situ bio-leaching project in narrow vein sulfide ores

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# Abstract

Mining is fundamental to exploit an extensive range of elements found in minerals and metals that are used in a variety of technologies in everyday life. As a result of their continuous extraction, most of the highly concentrated, superficial, and easily accessible ore deposits have been almost or entirely depleted by now. Moreover, to fulfill the needs and challenges of our society, such as green technology, renewable energies, microelectronics, and telecommunications, materials require a variety of specific elements whose global distribution is uneven and whose reserves in primary deposits are limited.

These are known as “strategic elements,” and are defined by their high economic importance and vulnerability to supply disruption. Their exploitation is imperative; however, the extractive industry is nowadays facing new challenges, as our society becomes more environmentally conscious. The continuous and reliable supply of raw materials is currently affected by more complex mineralogy, lower grades, higher depths, and rigorous regulations. Moreover, the aim to reduce the environmental footprint and social impacts generated is crucial.

Accordingly, conventional mining and processing methods are being highly criticized and constrained due to the large waste generation, energy consumption, and technical limitations imposed. Considering that the global trend is to move towards more sustainable development (SD), the industry’s obligation to improve conventional methods, develop new technologies, and in general, close the material loop becomes vital. Unfortunately, despite the recycling potential of these elements, new technologies, and government incentives, the recycling input rate is still not enough. For this reason, primary extraction not only will continue to be a part of the economy in the medium and long term, but also, strategic elements are not yet part of the circular economy (CE). Hence, CE principles and their implementation are starting to become more critical for the mining industry as a whole to abide by the SD requirements.

Consequently, given the massive reserves of strategic metals in medium and low-grade ores, a promising way to deal with the previous issues could be applying alternative methods, such as bio-hydrometallurgy and in-situ leaching (ISL) technology. It transforms insoluble metals into an aqueous solution employing bacterial leaching; afterward, the metals are selectively separated by solvent extraction and further purified by electrolysis. Among the principal benefits, this process is advantageous, as it consists of mineral exploitation without primary waste production, that is, without rock extraction: a substantial waste reduction makes this technology valuable for present and future mining activities.

To prove this idea, a framework to measure the mineral exploitation flows of mining methods based on material flow accounting (MFA) was developed and discussed in this paper. This framework is focused on CE principles and conservation of non-renewable resources. Therefore, a set of relevant material flow indicators for mining methods is implemented. Accordingly, for a defined deposit, in-situ bioleaching is compared to a conventional mining method, primarily in terms of productivity, the efficiency of recovery, and environmental impacts. Finally, the outcome of the analysis shows the benefits and disadvantages of each method related to the SD concept.

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# Abbreviations

| | |
|---|---|
| **ANFO** | Ammonium Nitrate Fuel Oil |
| **AZO** | Aluminium-doped Zinc Oxide |
| **BHMZ** | Biohydrometallurgical Center for Strategic Elements |
| **CE** | Circular Economy |
| **CSTR** | Continuous Stirred Tank Reactor |
| **CIGS** | Copper-Indium-Gallium-Diselenide |
| **CRM** | Critical Raw Materials |
| **ECI** | Economic Importance |
| **EW-MFA** | Economy-wide Material Flow Accounting |
| **EOL** | End-of-Life |
| **ECW** | Energy Consumption per Worker |
| **E-IN** | Environmental Inefficiency |
| **EC** | European Commission |
| **EU** | European Union |
| **EI** | Extraction Intensity |
| **EP** | Extraction Productivity |
| **FPD** | Flat Panel Display |
| **FTO** | Fluorine-doped Tin Oxide |
| **GE** | Germanium |
| **IN** | Indium |
| **ITO** | Indium Tin Oxide |
| **IR** | Infrared Radiation |
| **ISL** | In-situ Leaching |
| **ISR** | In-Situ Recovery |
| **LED** | Light Emitting Diodes |
| **LCD** | Liquid Crystal Display |
| **LHD** | Load-Haul-Dump |
| **MFA** | Material Flow Accounting |
| **MES** | Metal Sulfides |
| **PV** | Photovoltaic |
| **PDP** | Plasma Display Panel |
| **PET** | Polyethylene Terephthalate |
| **RMR** | Rock Mass Rating |
| **ROM** | Run of Mine |
| **SR** | Supply Risk |
| **SD** | Sustainable Development |
| **TRL** | Technology Readiness Level |
| **TAC** | Total Air Consumption |
| **TAE** | Total Air Emissions |
| **TDW** | Total Development Works |

| | |
|---|---|
| **TEC** | Total Energy Consumption |
| **TMP** | Total Material Processed |
| **TP** | Total Production |
| **TWRG** | Total Waste Rock Generation |
| **TWWG** | Total Wastewater Generation |
| **TWI** | Total Water Input |
| **TWR** | Total Water Recycled |
| **USA** | United States of America |
| **USGS** | U.S. Geological Survey |
| **VA** | Value-added |
| **WPB** | Water Pressure Blasting |
| **WRR** | Water Recycling Ratio |
| **WP** | Worker Productivity |

## Units and Symbols

| | |
|---|---|
| **a** | Annum |
| **C** | Celsius |
| **cm** | Centimeter |
| **°** | Degree |
| **GJ** | Giga Joule |
| **g** | Gram |
| **h** | Hour |
| **kg** | Kilogram |
| **kW** | Kilowatt |
| **L** | Liter |
| **MJ** | Mega Joule |
| **MT** | Mega tons |
| **$m^3$** | Cubic meter |
| **$m^2$** | Square meter |
| **m** | meter |
| **mm** | millimiter |
| **min** | Minute |
| **ppm** | Parts per Million |
| **s** | second |
| **t** | Ton |
| **US$** | United States Dollar |

# 1 Introduction

## Background

The extraction of raw materials has been central to humankind's development through time [1] . They are fundamental to produce an extensive range of products used in a variety of technologies in everyday life [2]. As a result, most of the highly concentrated, superficial, and easily accessible ore deposits have been almost or entirely depleted by now. Moreover, to fulfill the needs and challenges of our society, for instance, green technology to grow towards a low carbon industry, renewable energies, microelectronics, telecommunications, and others; materials require a variety of specific elements whose global distribution is uneven and reserves in primary deposits is limited [3]. Even though all raw materials are vital, some of them are of more concern than others [4]. Within the context of the European Union (EU), the so-called "strategic elements" refer to a defined group of materials which, due to several reasons, *"are both of high economic importance for the EU and vulnerable to supply disruption"* [5]. These elements are essential for three main reasons: Firstly, they are linked to all industries across every supply chain stage. Secondly, they are essential to technological progress. Lastly, they are closely related to the environment, namely clean technologies, for which they are still irreplaceable.

Furthermore, sustainable and undisrupted access to these elements must be carefully assessed to ensure a steady economy. The security of the supply of these elements is linked with their geological availability, i.e., average concentration on earth's crust. In the same way, the geographical allocation is crucial; for example, in the global spectrum, China provides 95% of rare earth elements, and South Africa is responsible for approx. 83% of platinum group metals. As a consequence, scarcity or monopolistic control of strategic elements makes them more likely to be considered as critical [2, 6]. Strategic elements such as Indium and Germanium have an average concentration in the earth's crust of 0.05 and 2 ppm, respectively. As many minor metals, they are widely dispersed and not found in enough concentrations to be mined solely for their extraction, and as in the case of Germanium, they do not occur in their elemental state in nature. Accordingly, they are mostly recovered as a by-product of other mining operations [7]. In turn, another pertinent issue is the fact that the extraction and further processing of pertinent metallic minerals are well-known to be a significant source of environmental heavy metal pollution and are frequently related to negative social impacts [3, 8]. The waste generated from the extractive industries is one of the most abundant waste streams within the EU [9]. It involves overburden, run-of-mine rock, discard, slurry, and tailings from the extraction and beneficiation processes [10]. Nowadays, the global mining industry is facing new challenges as our society becomes more environmentally conscious. The continuous and reliable supply of raw materials is currently affected by more complex mineralogy, lower grades, higher depths, and rigorous regulations. The latter, aiming to reduce the environmental footprint and social impacts generated. As a result, conventional mining and processing methods are being highly criticized and constrained due to their large waste generation, energy consumption, and technical limitations.

Today, there is a global trend to move towards more sustainable development [11]. This raises the industry's obligation to improve conventional methods, develop new technologies, and in general, close the material loop. Given the massive reserves of strategic metals in medium and low-grade ores, an auspicious way to deal with the previous issues could be applying alternative methods such as bio-hydrometallurgy as in-situ leaching technology. This technology has been developed mainly for those types—low-grade—of ores. It transforms insoluble metals into an aqueous solution employing bacterial leaching; afterward, the metals are selectively separated by solvent extraction and further purified by electrolysis [12]. Among several benefits, this process is most advantageous for it consists of mineral exploitation without primary waste production, that is, rock extraction. This substantial waste reduction improvement makes this type of technology valuable for present and future mining activities.

## Project Motivation

One of the most critical challenges facing our society today relies on the continuous development of new technologies to satisfy humanity's needs. Meaning that, in general, the manufacturing and refining industries are more relevant to the global industry when compared with the extractive industry. However, to compensate, mineral materials can be recycled, and in this manner, they can be kept as secondary resources to close the material loop [3]. Today, several strategic elements have a high technical and economic potential to be recycled. Additionally, governments are actively creating incentives and implementing regulations to advocate towards a circular economy. Despite all the efforts, the recycling input rate is insufficient so far. It is due to numerous factors: some recycling technologies are still not economically competitive and especially for strategic metals are hampered by dissipation; secondary supply for many strategic elements is confined in long-life goods, for instance, solar electric applications, which delays the manufacture-recycle timeline and accordingly has negative repercussions in present recycling input rates [13]; the current recycling rates cannot cope with the unceasing increase on demand of these elements. Consequently, the industry is facing crucial technical and economic challenges [3, 14].

In terms of sustainable development, reducing primary resource consumption—ergo, mining activities—is a condition to protect future generation's development [11]. However, it would be naive to believe that end-of-life (EoL) products recycling could utterly replace primary extraction [15]. As a result, the strategic elements value chain is not entirely and homogeneously covered by the industry. Likewise, it can be said that they are not yet fully part of the circular economy. Given the fact that primary extraction is still fundamental for strategic elements, and since they are considered crucial to the modern economy, the world's trend is headed for more sustainable ways to extract them. The latter, to ensure a proper supply while abiding SD principles. Due to the increasing development of more in-depth, complex, fine-grained, low-grade ore deposits, mining through conventional methods will keep generating several issues: increase of the stripping ratio, which causes higher waste generation; rise in energy use; higher mining costs; lower revenues, for there is lower ore percentage in each block; further environmental consequences, which in turn will lead to socio-economic problems. Therefore, the urgency for the mining industry to improve has become evident. Amongst a handful of innovation programs to find "more sustainable" mining methods, one encouraging initiative has been developed by the TU Bergakademie Freiberg. It established the "Biohydrometallurgical Center for Strategic Elements" (BHMZ) to promote interdisciplinary research along the bio-hydrometallurgical process to extract Indium and Germanium from sulfide ores. Within the university's own "Research and Educational Mine" facilities, an alternative mining and processing method called bacterial in-situ bioleaching is being tested on a small scale [16]. When this method is implemented industrially, it will aspire to mitigate several technical, economic, and environmental problems for which conventional mining is currently accountable. As a matter of fact, according to the Horizon 2020 Framework Program, it could be argued that the technology readiness level (TRL) of this method is around six. Thus, meaning that the technology has been demonstrated in a relevant environment [17]. Nevertheless, the method as a whole must achieve a TRL of nine to be competitive in the industry. Since there remains much to be done, this work is expected to contribute to BHMZ research. Furthermore, it will provide additional information to increase the mining method's TRL to support its further upscaling.

## Aim of the research

There is a broad consensus on the utmost importance of sustainable development nowadays. SD is one of the primary goals to ensure a thriving future for our society, especially within the EU. When exploring potential opportunities, in-situ recovery (ISR) through microbes can be considered a promising approach. Overall, this thesis intends to contribute to the industry's purpose to meet "sustainable mining" and, in turn, to go along towards SD. Hence, there is a necessity to know the current summary of the strategic elements situation, the main weaknesses and restrictions of the conventional mining industry—mineralized "waste rock" management—and its consequences. The former, to be able to understand the inevitable increase in demand for these elements and why there is a need to change the way to extract them.

Secondly, in broad terms, the scope is to illustrate how circular economy principles can be applied to the mining industry, not only within the material loop but also at the mine site level. The former, to grant the mining industry a greater understanding of how it can have a place in the new world of CE. For this purpose, the circular economy concept will be introduced. It is essential as well to comprehend its final goal, importance, and the way how it has been implemented in the European industry. Moreover, the mining industry's effort and progress to meet the circular economy objectives must be clearly stated.

Another objective is to evaluate the alternative method known as in-situ bioleaching. This thesis will display the potential of this approach to successfully recover strategic elements from medium-to-low-grade ores in a more sustainable way [16]. Hence, aiming to demonstrate an improvement in several areas such as waste generation, energy consumption, mineral recovery efficiency, and emission generation. All of this, in order to provide further proof on this method and its large-scale feasibility to be implemented on an industrial scale, and to become not only competitive when compared with traditional methods but also advantageous in different aspects when assessing its sustainability.

To achieve the objectives mentioned above, the small-scale in-situ bioleaching process that is being tested at the moment on the BHMZ facilities within the Research and Educational Mine "Reiche Zeche" will be evaluated in various aspects, which are mainly related to metal productivity, waste generation, expenses, and environmental protection. Subsequently, it will be compared to a conventional mining method to establish its advantages and drawbacks to assess its likelihood of up-scaling.

This thesis was developed as a result of the continuous pursuit to make the base and precious metal mining less damaging of the environment, less demanding of energy in a modern world that is much concerned about environment and resource preservation [18]. Similarly, this work responds to a highly criticized mining industry. Therefore, it states the considerable efforts that are currently taking place to better the mining and processing methods and technologies, without compromising the present provision of these highly essential elements and increased harm to the environment.

## Approach

To fulfill the aims and objectives previously mentioned, the evaluation that will be carried out in this work is explained here. After this, a literature review concerning all the previous necessary knowledge will be performed. To this end, a careful introduction to the problem is required, and accordingly, the following procedure will be undertaken. First of all, an explanation of the relevance surrounding the strategic elements and the different manners to exploit them is imperative. Next, the involvement and goals of the mining industry and, in particular, medium-to-low-grade ore exploitation to comply with the circular economy objectives must be provided. Then, a brief explanation of the in-situ bioleaching method, along with its applicability and state of the art, will be made. During this work, a framework to model mineral exploitation flows of mining methods will be developed with the use of Material Flow Accounting (MFA) indicators applied to the mineral industry to allow to compare minability and extraction efficiency of in-situ bioleaching against a conventional method. Following this, the case of study will be presented with an overview of the BHMZ project, the "Reiche Zeche" mine, and the description of the process taking place there. Afterward, an introduction to the conventional method occurring on an equivalent mine—the name of the project cannot be displayed due to a confidentiality agreement—will be introduced. Finally, to perform the assessment, it is essential to extrapolate the data obtained from the laboratory scale in-situ bioleaching process to the conventional mine size mentioned above. As a result, the assessment through the developed framework will be conducted comparably and validly.

# 2 Strategic Elements mining

The mining of strategic elements employing conventional methods is at the edge of not being sustainable anymore, declining the industry. It is mostly due to the decreasing grade of ore deposits, which in turn, downgrades the value of deposits. At the same time, it increases environmental damage and provides ever-smaller valuable metal outputs. Recalling not only the rising ecological concern of society but the economic viability of metal extraction and contemplating the increasing importance of strategic elements to the economy, the industry is continuously researching and developing new technologies to address these issues. With this in mind, leaching technology was established. Leaching is a low-cost technology used in the mining industry to recover strategic elements from specific minerals, mainly with the help of selective chemical substances [19]. For instance, sulfuric acid or sodium hydroxide solvents are used to leach oxides, ammonium hydroxide is used for carbonates and sulfides, and cyanide solvent for precious metals.

Furthermore, leaching can be executed by three principal methods (Figure 2.1) [20, 21]. The first one is tank leaching, which is used for the higher-grade ores. The ore is inserted as a slurry in a continuous stirred tank reactor (CSTR), where it is mixed with the lixiviant to obtain the valuable metals. This process can be done at atmospheric pressure and ambient temperature or in pressurized tanks, which increases the temperature to improve the leaching rate [22, 23]. The second one and most used is heap and dump leaching; it is done at ambient temperature and atmospheric pressure. It is carried out on semi-low-grades—grade is high enough to allow the ore to be conveyed to surface for treatment—, and it is widely used since this type of ore is already being mined in vast amounts. For example, in 2014, around 17% of global gold production was by way of heap leaching [24]. The fundamental difference between heap and dump leaching is that the first is a pre-planned process, where ore conditions are modified to optimize the leaching operation (such as additional crushing) [25]. While dump leaching is performed on rejected material—ore beneath the cut-off grade—that was carried outside during normal mining operations and is placed in dumps at the mine site [26]. Thirdly, in-situ leaching is practiced on the high depth and low-grade ores, where extraction and surface treatment is not economical. It consists of leaching the ore without excavating it, signifying that the lixiviant flows through the fractured ore body, dissolving the targeted elements into an aqueous solution, and subsequently pumped to the surface for further filtration [27].

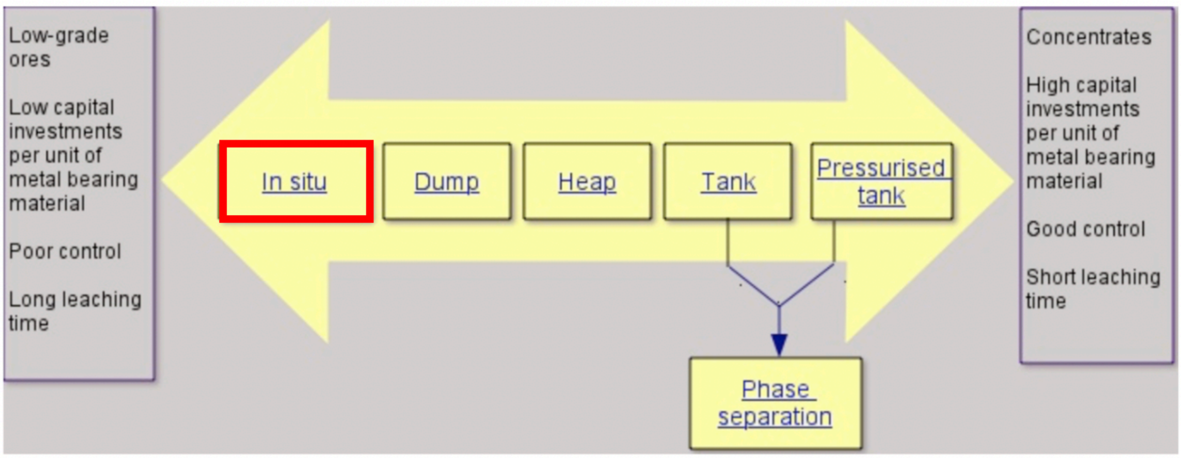


Figure 2.1 Leaching methods [28]

These methods have proven the capability of the mining industry to adapt to constant change. However, despite the measures adopted, the problem of highly dangerous chemical use perseveres. In light of this, the use of microorganisms—biotechnology—to reduce the environmental burden of toxic substances has become of great importance. Nowadays, this technology has been integrated into the previously mentioned methods to better their eco-friendly performance [29]. Under such circumstances, biohydrometallurgy as an in-situ leaching method, also called in-situ bioleaching, is gaining attention for its potential to extract low-grade ores at a low environmental cost lucratively. Consequently, this chapter will focus on the definition of low-grade ores as well as the economic relevance of strategic elements to provide an overview of why the use of in-situ bioleaching has potential for future industrial implementation.

## 2.1 Low-grade ore (Mineralized waste rock management)

### 2.1.1 Waste rock definition

Globally, the exploitation of minerals is an ever-increasing industry. At the same time, high-grade ores are being depleted, thereby inducing the ore grades extracted to diminish over time. Thus, for a profitable business, it must be acknowledged that there is a specific grade below which is no longer profitable to mine any given mineral despite its presence in the ore. As well, it is essential to recall that the market price is assessed based on the present demand and supply [30]. In the light of this, ore grade evaluation for any specific deposit hinges not only on geological availability but also by current technology, and economic, environmental, social, and political regulations [31]. That being said, for this work, waste rock is composed of rock and targeted minerals in concentrations so low (non-mineralized or mineralized waste rock), for which cost-effective recovery is not possible [32]. Hence, unfeasible extraction can be whether due to economic reasons—low market price—or extremely low-grade. Waste rock arises in different stages of the mining process and throughout the life of the mine. Typically, it comprises granular and broken rock, ranging from large boulders to fine sand, which is determined by the formation and mining methods used. Besides, waste rock geochemistry depends on the geology of each mine; it can even change within a single mine if diverse lithologies are mined. Often, in metal mines, the waste rock generated contains sulfidic and other common toxic materials aside from the targeted mineral [33]. Yet, not all waste is considered damaging for the environment, i.e., inert waste rock, which is allowed to be used as building materials.

Moreover, potential impacts depend always on the geo-characteristics of the deposit and its geochemistry. Accordingly, the most severe consequences caused by waste rock are environmental impacts, for these are usually followed by economic, political, health, and social impacts. Firstly, waste rock can be the source of physical disruption of the landscape, being the leading visual and aesthetic impact of mining. Similarly, the design of waste piles must be carefully engineered, thus preventing any accidents due to the instability of the piles, which can cause further issues. Secondly, waste rock can cause soil contamination owed to the erosion-driven concentration of metals in stream sediments. This situation has the potential to generate considerable damage since these metals are considered available in the environment.

In the same way, waste rock can be the source of water contamination through acid rock drainage, since it is relatively common to find sulfide minerals in metal mines (frequently pyrite, that is, iron sulfide). When these minerals get in contact with air and water, they experience an oxidation process and produce acidic conditions. If water is acidified and left uncontrolled, it can reach other water streams, thus harming the environment. Thirdly, the mining and refining processes can generate gas and particulate emissions that are released to the atmosphere. This situation may induce implications on human health, and if combined with rain, acid rain could develop, leading to the consequences already mentioned for acidic water and soil. Finally, mining carries public safety impacts. Regarding this, there is a hazard of ground subsidence or an abrupt collapse [34]. As it was already stated, to avoid or mitigate any of these impacts, there are economic, political, and social repercussions and actions to take place.

### 2.1.2 Types of waste rock

According to the provisions of Directive 2006/21/EC of the European Parliament on the management of waste from extractive industries, regarding mining activities, there are two main categories [35]:

- Extractive waste derived from the excavation of mineral resources: i.e., overburden, inter burden, and waste-rock.

Nonetheless, it is compulsory to clarify the definitions of the previously mentioned terms. Overburden and inter burden refer to all the soil and rock above and in-between the seams of the ore body. In contrast, waste-rock is the bedrock extracted—whether it is from open-pit or underground mines—that has a grade lower than the cut-off-grade of the targeted mineral and thus is not of economic interest [36].

- Extractive waste derived from the mineral processing of mineral resources: i.e., tailings, waste generated from cleaning minerals, waste from stone cutting and sawing, waste sand, waste gravel, or crushed rocks.

The fundamental term, in this case, is tailings, referring the coarsely and finely residual material that remains after the mill process—beneficiation operation—, that extracts the valuable elements from the ore. Correspondingly, the physical and chemical characteristics of the tailings vary based on the ore characteristics, and the type of beneficiation method used [33].

Waste rock is a dynamic concept; it is primarily governed by economic restrictions and, as such, in-situ medium-to-low-grade ore, can be diversely classified—as waste rock or ore—depending on the current circumstances of each mine. For instance, a frequent situation occurs where mining operations take place on low-grade ore (mineralized waste rock), whether it was extracted or is still in-situ, that was thought-out waste by older mines [37]. The decision to classify a specific volume of material as waste or ore, besides the economic reasons, is also subjected by the available technology, environmental regulations, and possible social impacts. Consequently, given the constant development of more rigid environmental constraints, there is an opportunity for in-situ medium-to-low-grade ore to be treated ore instead of mineralized waste rock. It is due to the currently available and developing technologies, which are allowing this type of ore extraction to be economically feasible while reducing environmental impacts. Given the above, the type of "waste rock" that will be further analyzed is medium-to-low-grade ore, which for this thesis purpose will be considered as ore from now on.

## 2.2 Strategic Elements

### 2.2.1 Definition

Raw materials are not only entailed for the manufacture of daily used products but are needed for sophisticated materials that are important to several innovative applications. Likewise, there is an increasing need for these advanced materials due to the development of more competitive and environmentally friendly technologies. Additionally, growing economies—due to an expanding population—and fast depletion of the earth's limited resources (in particular, highly coveted minerals and metals) are raising a concern about future material supply [3]. Equally, some other factors, including uncertainties in the global economic, social, and political scenarios, are causing price volatility and instability on some raw materials supply. As a consequence, ensuring reliable and unrestricted access to certain raw materials has become a significant challenge for national and regional economies with limited production and high dependency on imports, like the EU economy [38].

Bearing this in mind, the European Commission (EC) implemented the European Raw Materials Initiative, which outlines a strategy to address the issue of access to raw materials in the EU. This policy was built around three pillars that intend to:

- Guarantee a fair and sustainable supply of raw materials from international markets
- A secure sustainable supply of raw materials within the EU
- Promote resource efficiency and supply of secondary raw materials through recycling

A vital topic of the initiative was to define a list of critical non-energy and non-agricultural raw materials through a criticality assessment. The first list was published in 2011, and it is updated every three years. Hence, it is crucial to regularly and adequately review the criticality of raw materials utilizing the methodology developed by the EC [39, 40]. The two main evaluated parameters are economic importance (ECI) and supply risk (SR). ECI depicts the relevance of the material in end-of-use applications and the value-added (VA) of manufacturing areas for the EU economy.

On the other hand, SR indicates the risk of a disruption in the EU supply of the material. It considers the amount of primary supply from raw materials producing countries. Depending on the EU import reliance (ECI), both global suppliers and the countries from which the EU acquires its raw materials are considered. SR is measured at the most critical stage of the material, that is, extraction and processing. Recycling and substitute materials are treated as risk-reducing actions [2]. The list is settled with the results of the assessed materials that reach or surpass the thresholds for both parameters defined by the EC (Figure 2.2). Therefore, Critical Raw Materials (CRM)—also called Strategic Elements— are raw materials of significant economic importance for the EU, their supply is associated with high risk, and there is a lack of feasible substitutes for them [41, 42]. Strategic elements are vital to the EU, mainly due to three reasons. First of all, they are associated with all the supply chain stages in a wide range of industrial sectors—including military, automotive, medical, and electronics—and for a variety of applications. Secondly, Strategic Elements are linked to current technologies, which are unceasingly increasing the number of raw materials that ensure high quality and functionality on some features. For instance, lightweight, small size, higher processing velocity, larger memory, long-lasting batteries, among others, are highly valued qualities. Lastly, these elements are related to the environment, as well. They are widely used in clean technologies and often found to be irreplaceable for some applications, namely solar panels, electric vehicles, and wind turbines [2].

In spite of the vast amount of critical raw materials (78 individual materials [38]), only the most relevant elements for this work, which are Indium (In) and Germanium (Ge), will be mentioned and further analyzed in this thesis due to simplicity issues.

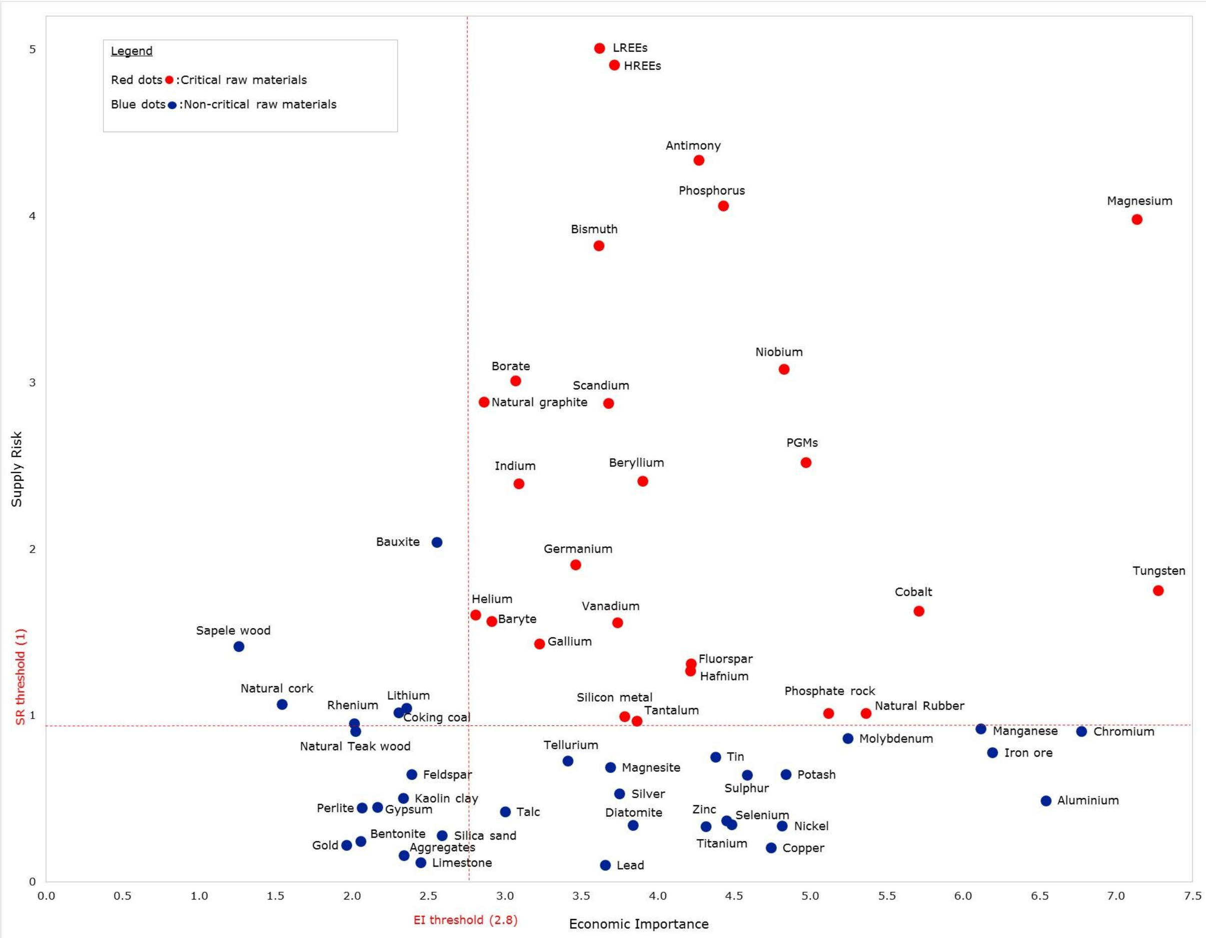


Figure 2.2 Critical Raw Materials for the EU of 2017 according to the criticality assessment [38]

## 2.2.2 Indium and germanium profiles

### 2.2.2.1 Indium (In)

Indium exists in minerals of other metals since it does not occur in its elemental state, as it is shown in Figure 2.3, where the principal elements are in the inner circle. Associated elements are located in the outer rings at distances proportional to the percentage of their dependence (from 100 to 0%) to the principal component. Thus, indium is extracted as a by-product of other mining and processing operations. Globally, it can be found in lead, copper, and tin minerals (approx. 5%). However, the principal source of indium is zinc concentrates (approx. 95%), being the most relevant sphalerite [43]. It is recovered from the residues produced throughout the smelting of zinc concentrates. It has been determined that about 35% of the indium mined from zinc concentrates—excluding China and Russia—is refined. The 25 - 30% is accumulated in waste as it has been estimated to be harder to recover due to iron contaminants, and 40 - 50% is lost in mostly in zinc refineries who cannot process indium because it is seen as an impurity in zinc metal [44, 45]. It is essential to point out that the indium concentrates in zinc ores are complicated to process caused by other by-products or “contaminants” such as cadmium and antimony. As a consequence, Indium refining still has technical issues and, thus, is economically feasible only if it has a high price [7].

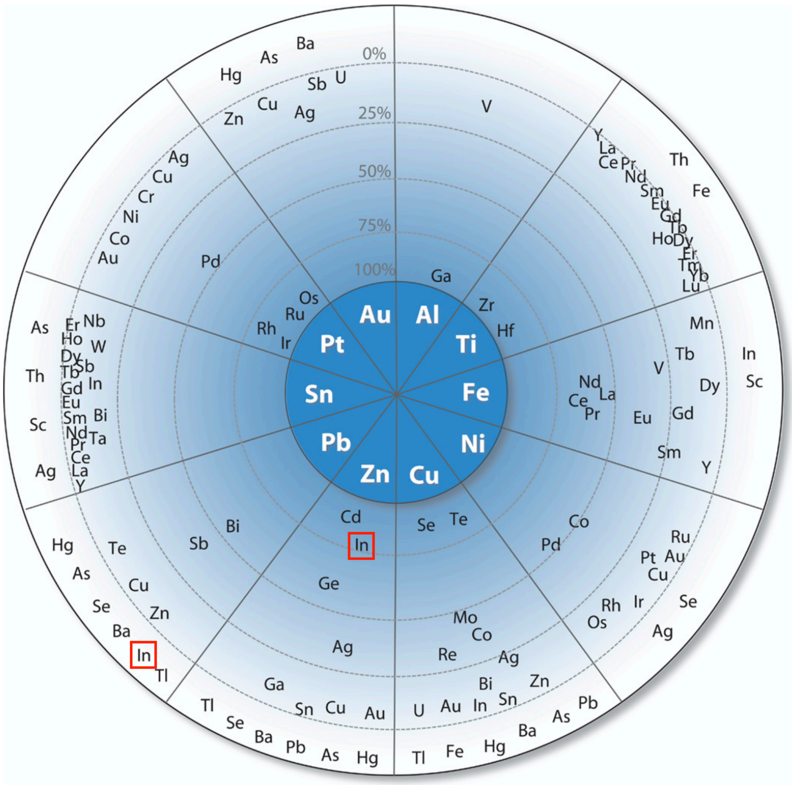

Figure 2.3 Wheel of metal companionality – Indium [46]

*World resources, production and supply data*

Since indium is mostly extracted as a by-product, its reserves and resources are estimated based on zinc and copper resources and reserves with an average concentration of indium. Additionally, because of its scarcity and criticality, up-to-date information about resources and reserves is limited. Roughly, it can be said that global resources from zinc ores are about 95,000 t using an In concentration of 50g/t. Additionally, resources from copper ores were 30,000 t in 2012 with an Indium content of 10g/t (Table 2.1). The countries with the largest reserves are China, Peru, the United States, Canada, and Russia [43, 47].

Table 2.1 Estimated global indium resources and reserves by source in 2012 (t) [43]

| Type of ore | Zinc | Copper | World |
|---|---|---|---|
| **Resources** | 95,000 | 30,000 | 125,000 |
| **Reserves** | 12,500 | 6,300 | 18,800 |

According to the U.S. Geological Survey, in 2018, the total global refinery production of indium was about 755 t [48]. As seen in Table 2.2, it is clear that the leading producer of indium is China, who is accountable for nearly 40% of global production, whereas, in the EU, the primary producers are France and Belgium. It is important to note that, since indium is not found in enough concentrations for it to be a significant commodity in deposits, its production depends strongly on zinc production [43]. Although there is potential to expand indium production, it is still a crucial decision, for indium represents a meager percentage (around 3%) of the total earnings. It has been estimated that to justify beneficial indium extraction, its content within the concentrate should be at least around 100 ppm. Undoubtedly, feasible indium production presupposes substantial investment in refining technologies, as well as performing active sourcing to assure a proper indium content within the zinc concentrates [7].

Table 2.2 Refinery indium production of 2017 and 2018 (t) [48]

| **Country** | **Refinery production** | |
|---|---|---|
| | **2017** | **2018** |
| **China** | 287 | 300 |
| **Republic of Korea** | 225 | 230 |
| **Japan** | 70 | 70 |
| **Canada** | 67 | 70 |
| **France** | 30 | 50 |
| **Belgium** | 20 | 20 |
| **Peru** | 10 | 10 |
| **Russia** | 5 | 5 |
| **World total** | 714 | 755 |

*Market, demand and price*

Over the period 2010 - 2018, the EU was a net exporter, this mostly due to the significant increase in exports in 2011. During the following years, imports and exports suffered a drastic reduction until they reached stable values of 45 - 55 t per year. Solely referring to imports, the EU has imported about 82 t per year of powdered and unwrought indium during the past eight years (Figure 2.4). Furthermore, the major suppliers for the EU are China and the USA, who provided the EU with 20 t and 7 t in 2018 (Figure 2.5 a). Additionally, crude indium is exported from the EU for high purity refining mainly to Japan, exporting nearly 30 t and also to one of its major suppliers, USA, exporting almost 10 t in 2018 (Figure 2.5 b) [7].

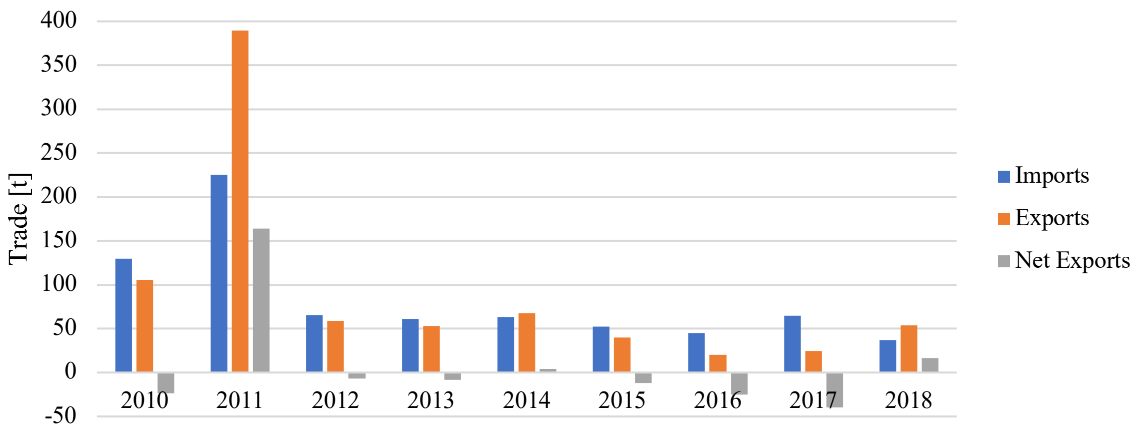


Figure 2.4 EU trade for unwrought and powdered indium from 2010 to 2018 [49]

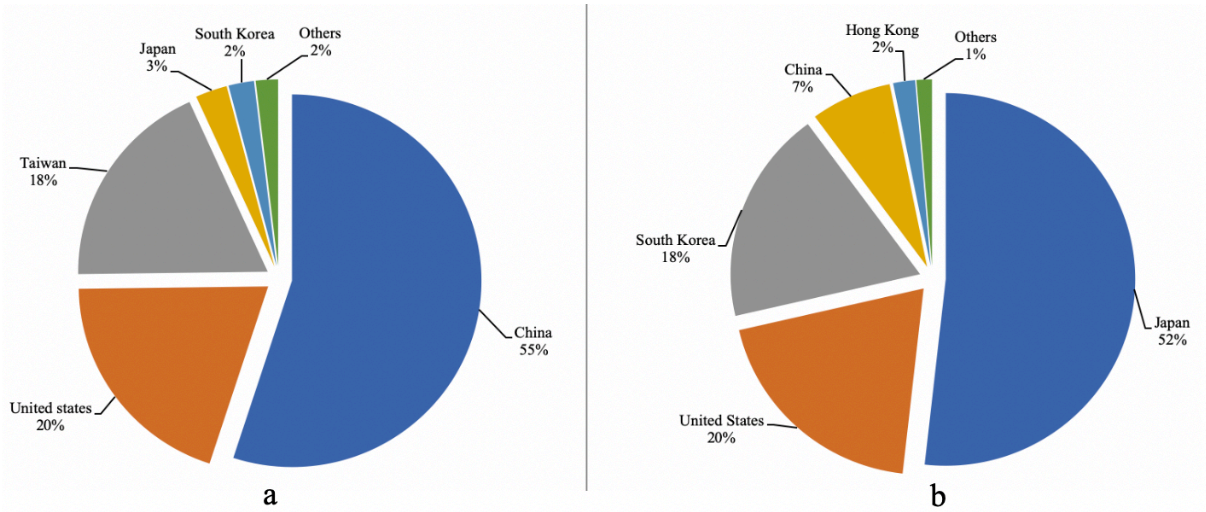

Figure 2.5 EU imports (a) and exports (b) of unwrought and powdered indium in 2018 [49]

Indium consumption has grown steadily over the last years [50]. In 2012, the world's total demand was around 1550 t, as was derived from the Liquid Crystal Display (LCD) industry [47]. The EU indium consumption of that same year was estimated to be 54 t, which represents approximately 3% of global consumption [44]. Moreover, the current primary production capacity is higher than the effective production, meaning that possible future increases in demand can be met in the short term. Nevertheless, indium demand is likely to grow at a much faster rate in the coming years due to its use in diverse applications, thus encouraging improvements in zinc-refining and recycling processes [7].

As it was already mentioned, the indium supply is heavily dependent on zinc production. With an increasing number of applications that use it as raw material, its price tends to be volatile [7]. Indium price rose until its maximum peak of over US$ 1,000 in 2005. Subsequently, it dropped after the global economic crisis in 2008 [51]. Nevertheless, they displayed a considerable recovery in the following years and reached prices of about US$ 800 by 2011. From then onwards, prices were steady and even raised to almost US$ 1000 through stockpiling at the Fanya Metals Exchange until its debacle in 2015. From that moment on, prices decreased to roughly US$ 300 per kilogram and have been maintained relatively cheap up to now (Figure 2.6) [43, 51].

Figure 2.6 Historical price volatility of indium 2015-2020 [52]

*Uses and place in the circular economy*

The leading uses of indium are principally in the form of indium-tin-oxide (ITO), low-temperature solder, and III-V semiconductor materials [45].

First of all, indium is widely used in thin-film ITO form due to its transparency and electrical conductivity. It is mostly used to manufacture flat panel displays (FPDs). Although the most common use is on liquid crystal displays (LCDs), it is also used for plasma display panels (PDPs) and touch screens. ITO was accountable for 56% of the total global consumption in 2012 [47]. Secondly, 10% of indium is used as a lead-free solder; it can be used as an indium-containing allow or as a pure metal. In is generally used for this purpose as a result of its high malleability, ductility, high thermal conductivity, and low melting point; thus, it can improve the thermal fatigue of welds [43, 45]. Thirdly, about 8% is consumed in photovoltaic (PV) applications in the form of copper-indium-gallium-diselenide (CIGS) solar cells. This end-use is relatively recent, and as such, it covers a small portion of the global indium consumption. Nonetheless, it has been estimated that the CIGS market will grow significantly in the future on account of its improvements in efficiency and material intensity when compared to silicon-based solar cells [7]. Finally, the remaining 26% of indium consumption is used in a wide range of applications; among them are thermal interface materials, batteries, compounds, light-emitting diodes (LEDs), and others [47].

Indium is mainly recycled from new scrap. In 2011, secondary production from new scrap was 63% of the total production of indium. It is owed principally to ITO recycling since it is the primary source of manufacture waste, which is predominantly generated in China, Japan, and South Korea, the leading producing countries. Due to the high inefficiency in the ITO sputtering process, only 40% of the input is indeed processed, thus, allowing high recycling rates [7].

There is an entirely different scenario when considering end-of-life or old scrap recycling. Worldwide, less than 1% of old scrap is recycled [43]. Additionally, according to the list of critical raw materials for the EU of 2017, the end of life recycling input rate of indium was 0% [53]. Several reasons cause the low-to-null rates of EoL recycling. First, there is low indium content in FPDs, which are the primary source of waste, and therefore, large amounts of waste and specialized infrastructures are needed to turn recycling feasible [54]. Secondly, for another large share of consumption—CIGS solar cells—, EoL recycling is not economically viable. It is principally due to the reason above—low indium concentration—but also because CIGS solar cells are relatively new in the market and are designed for long life spans, which limits the recycling efforts [7]. As a consequence, there is a constant investigation to develop possible substitutes. Regarding ITO, although currently there is no large-scale substitute, there are some alternatives, such as aluminum-doped zinc oxide (AZO) and fluorine-doped tin oxide (FTO), which are more affordable but at the expense of weaker performance [43].

Potential for future indium demand to augment has been observed, mainly guided by FPDs and PV industries. It has been assessed that PV applications could boost indium demand to 15% per year, whereas the expansion of zinc production will remain substantially lower, increasing at 1 - 3% per year [47]. It is crucial to consider the imbalance between a high share of primary production against small functional recycling (Figure 2.7). Given the preceding statements and considering the criticality of the material as well (Figure 2.8), there is a vital need to improve primary production from the zinc, lead, and other indium-containing deposits while reducing the negative impacts that its extraction implies.

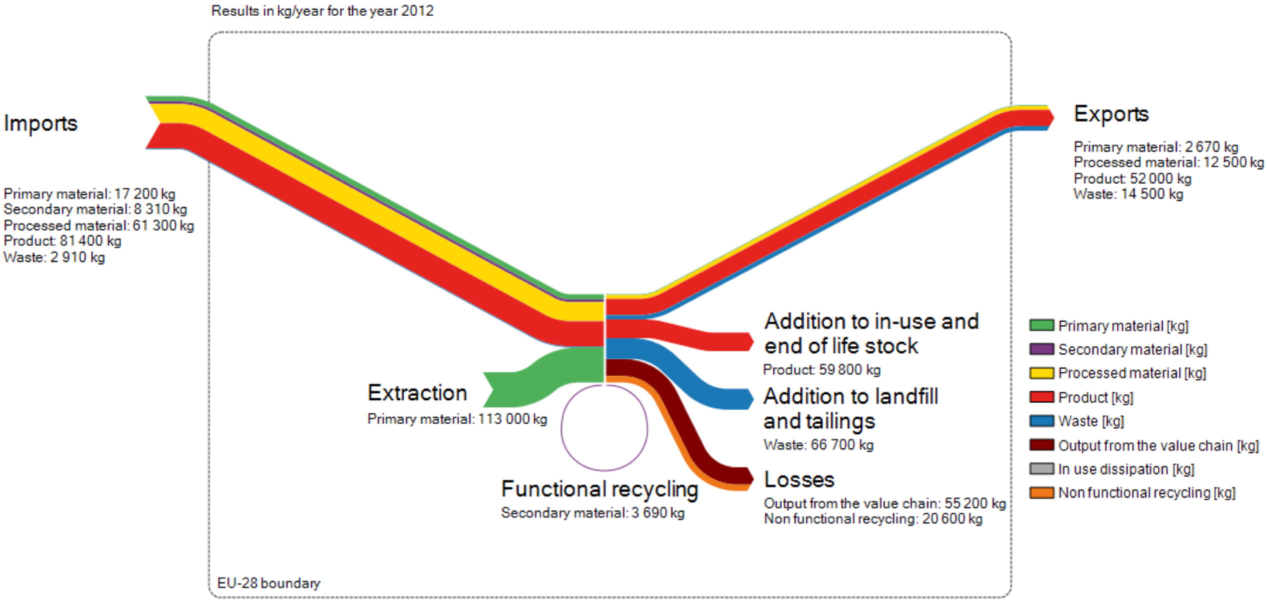

Figure 2.7 Sankey diagram for indium flow [44]

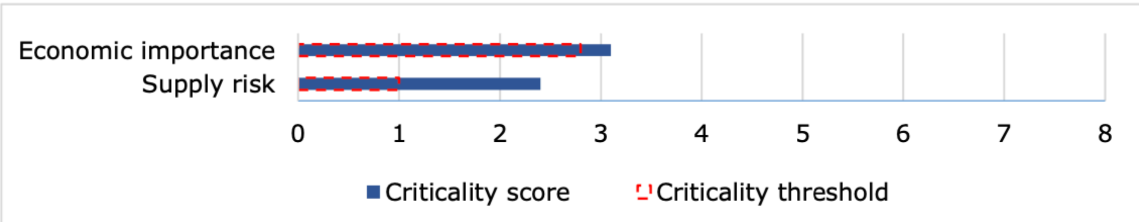

Figure 2.8 Criticality of indium to the EU [43]

#### 2.2.2.2 Germanium (Ge)

Germanium exists as a trace metal in several mineral ores, as it is shown in Figure 2.9 , where the principal elements are in the inner circle. Associated elements are located in the outer rings at distances proportional to the percentage of their dependence (from 100 to 0%) to the principal component. Moreover, only a few germanium minerals have been defined, being the most important germanite. It is primarily extracted as a by-product of zinc ore processing (approx. 75%). The secondary approach of recovery is from coal fly ash (approx. 25%), and China and Russia are the only countries that recover it from this source. Germanium production is highly dependent on zinc mining. On a global scale, merely 3% of Ge is refined from this source (only 12% of Ge mined outside of China, and Russia is refined and further used in the value chain) [7, 55]. Therefore, its market cannot respond rapidly to demand, and it is likely to be volatile. This demonstrates the possibility to increase production in the future.

There are two main reasons why Ge has such low refinery rates. First, it has been said that germanium extraction has negative implications on zinc recovery, harming the bulk income of refineries. Second, large germanium-zinc concentrates are required for germanium recovery to be economically feasible; this means a higher cost of sourcing the concentrate, which may not benefit the business [7].

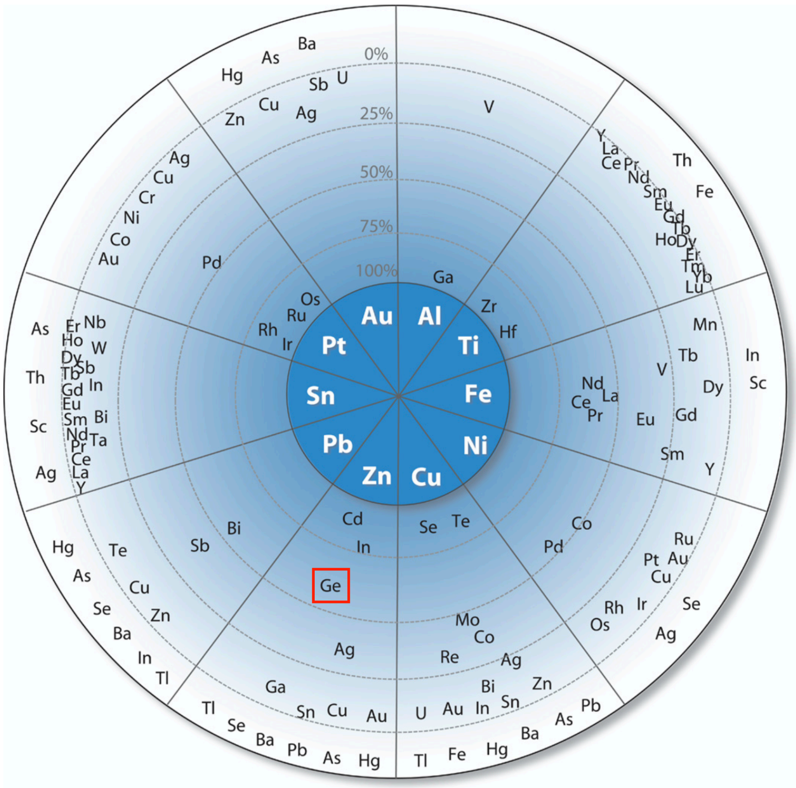


Figure 2.9 Wheel of metal companionality - Germanium [46]

*World resources, production and supply data*

First of all, it is essential to emphasize the fact that there is no single source of complete standardized evaluations for resources and reserves of germanium deposits. Different companies, governments, and organizations publish reports but commonly using a variety of reporting systems [43]. Additionally, because of its scarcity and criticality, up-to-date information about resources and reserves is limited. Stated the latter, germanium is mainly found in zinc and lead-zinc-copper sulfide ores [55]. Global resources are roughly 35,600 t, being 24,600 t in coal and 10,000 t in zinc ores (Table 2.3). World reserves of germanium are estimated as 8,600 t. In the EU, there are no reserves of germanium, and as a result, there is no production [44].

Table 2.3 Estimated global germanium resources by location and source in 2012 (t) [7]

| Country | Zinc ore and slag | Coal and coal ashes | Total |
|---|---|---|---|
| **Russia** | - | 17,500 | 17,500 |
| **China** | 4,200 | 6,660 | 10,860 |
| **Democratic Republic of Congo** | 3,750 | - | 3,750 |
| **USA** | 2,300 | 165 | 2,465 |
| **Namibia** | 530 | - | 530 |
| **Uzbekistan** | - | 180 | 180 |
| **Mexico** | 150 | - | 150 |
| **Ukraine** | - | 100 | 100 |
| **Canada** | 90 | - | 90 |
| **World Total** | **11,020** | **24,605** | **35,625** |

According to the U.S. Geological Survey, in 2018, the total global production of germanium recovered from all sources, zinc concentrates, coal fly ash, and recycled material was of about 120 t [55]. Recycling of Ge from old scrap—also called post-consumer scrap—has been increasing in the last decade. About 30% of the world's total production of germanium is derived from scrap. Due to the high-value of the refined material, the new scrap that comes from the manufacturing processes of fiber-optic cables, infrared optics, and others is retrieved and brought back to the production process [56]. As seen in Table 2.4, it is clear that the main producer of germanium is China, who is accountable for nearly 60% of global production.

Table 2.4 Primary and secondary germanium production of 2017 and 2018 (t) [55]

| **Country** | **Refinery production** | |
|---|---|---|
| | **2017** | **2018** |
| **China** | 60 | 75 |
| **Russia** | 6 | 6 |
| **Other countries** | 40 | 35 |
| **World total** | **106** | **120** |

*Market, demand and price*

Since the EU does not produce germanium, it is mostly an importer of this strategic material, generally having negative net imports over the years (Figure 2.10). It imports close to 13 t per year of powdered and unwrought germanium (without considering other substances containing Ge). Furthermore, the major suppliers for the EU are China and the USA, who provided the EU with 16.9 t and 2 t in 2018 (Figure 2.11 a). Additionally, unrefined germanium is exported from the EU mainly for high purity refining to its major suppliers, USA and China, exporting 3 t and 2.1 t in 2018 ( Figure 2.11 b) [7].

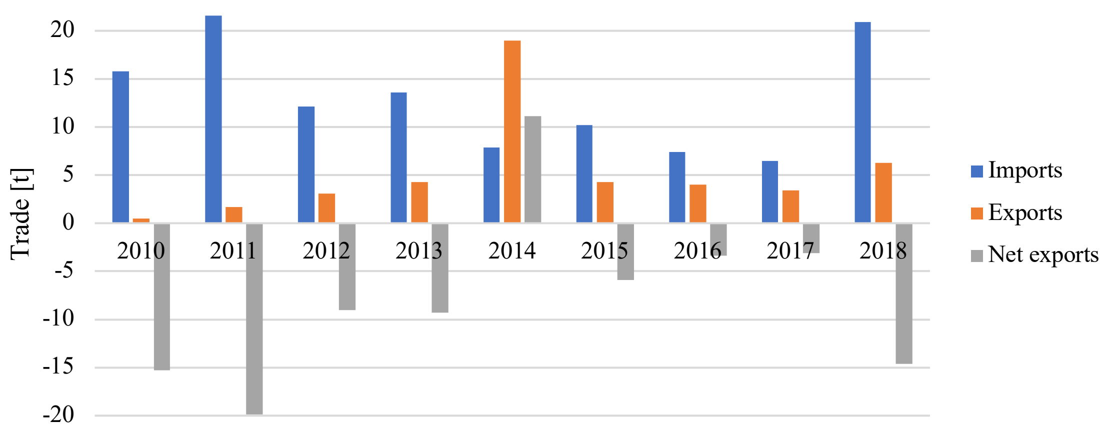


Figure 2.10 EU trade for unwrought and powdered germanium from 2010 to 2018 [57]

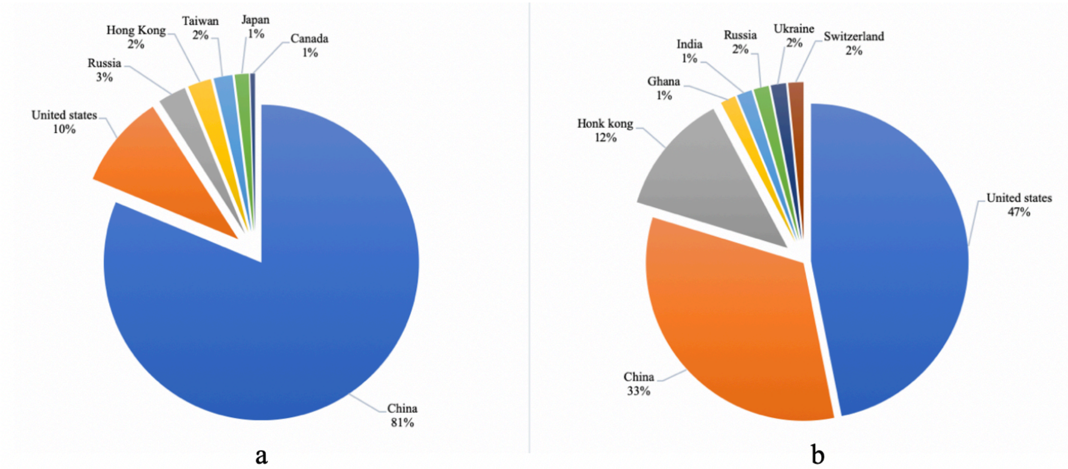


Figure 2.11 EU imports (a) and exports (b) of unwrought and powdered germanium in 2018 [57]

EU's demand for germanium processed materials was approximately 37 t in the 2010 - 2014 period, representing 25% of the world consumption [43]. According to the USGS, world germanium primary production has been lower than world consumption. Despite this, government efforts to increase recycling rates and occasional germanium releases from their stockpiles have led to an adequate supply.

The price of germanium has suffered high volatility over the years, as can be seen in Figure 2.12. During the first years of the XXI century, there was a continuous price decrease due to a reduction in demand and because of the implementation of recycling technologies and stockpile releases, until it reached its global minimum of US$ 380,000 per ton in 2003. Since then, prices have been rising steadily until the global economic crisis in 2008, which led to a general reduction in prices. Nevertheless, they displayed a considerable recovery in the following years. Between 2012 and 2015, prices have raised significantly, reaching its maximum peak of US$ 1.9 million in 2013 - 2014. The former was owed to the closure in 2012 of three Chinese germanium dioxide plants due to environmental issues and export tax on germanium dioxide from China, among other reasons. The price remained high until 2015 principally as a result of a speculative investors demand organized by a Chinese minor metals trading platform. After that, the trading platform collapsed, causing an important price decrease in the next years [43].

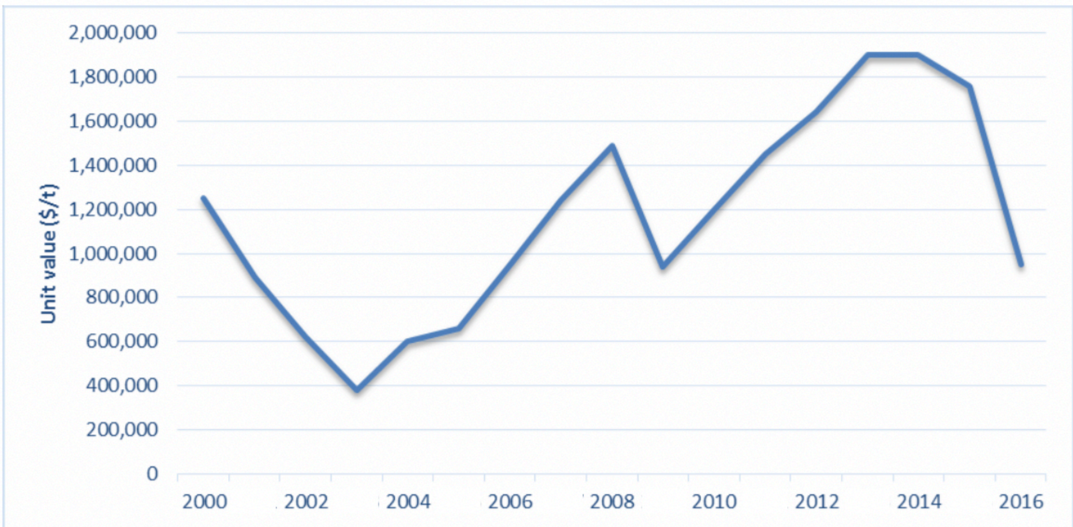


Figure 2.12 Historical price volatility of germanium in US$ per ton [43]

*Uses and place in the circular economy*

The main uses of germanium in the EU industry are infrared optics, fiber-optics, and solar cells. Similarly, it is used in metallurgy and chemotherapy. On the other hand, outside the EU, germanium is mostly used in electronic components and as catalysts for PET polymerization.

First of all, the greatest end-use of germanium in the EU is infrared optics, with a share of 47%. It is used in this industry to make lenses and windows for infrared radiation (IR)—because Ge is transparent to IR wavelengths—primarily for military applications such as night-vision devices. Apart from that, it is commonly used for medical diagnostics, satellite imagery sensors, and firefighting accessories. Secondly, 39% of germanium consumed is highly used in optical fiber applications. It is added in small amounts to pure silica glass to boost its refractive index and thus, avoid light absorption and signal loss. It is mainly used in telecommunications, and as a result of the accelerated pace of development of this industry, germanium demand has had a substantial growth as well. Thirdly, 13% of the total EU consumption of germanium is used on solar cells, either for the ground and satellites. Ge is used for these applications due to its improvement in size, weight, and efficiency when compared to silicon-based solar cells of about 25%. Finally, the remaining 1% of the germanium is used for gamma-ray detectors, metallurgy, and chemotherapy [43, 56].

The expensiveness of refined germanium stimulates recycling mostly as new scrap, which is the one that comes from production processes [43]. Worldwide, approximately 30% of the germanium consumed derives from recycling processes, such as windows from military devices. For example, about 60% of the metal used in the manufacture of optical devices is recycled as new scrap [55]. However, even though Ge recycling from old scrap such as fiber-optic cables has increased throughout the last decade, it is still insufficient [56]. Currently, functional recycling has been estimated to be close to 12%, while the end-of-life recycling input rate is barely 2% (Figure 2.13) [53]. It has been estimated that these circumstances will not improve in the future as a result of enormous dissipation and space applications, which will not allow the recycling of considerable volumes of material. In general, secondary germanium recovery is technically and economically complicated. Furthermore, although there have been investigations of viable substitutes and the fact that there are various alternatives for some applications, many of these are not efficient solutions, resulting in performance loss and low probability of implementation on an industrial scale [43]. All in all, since the forecast of world germanium demand, is to grow at about 4.4% per year [7], and the high criticality of the material for the EU (Figure 2.14), there is a vital need to improve primary production of this crucial material while reducing the negative impacts that its extraction implies.

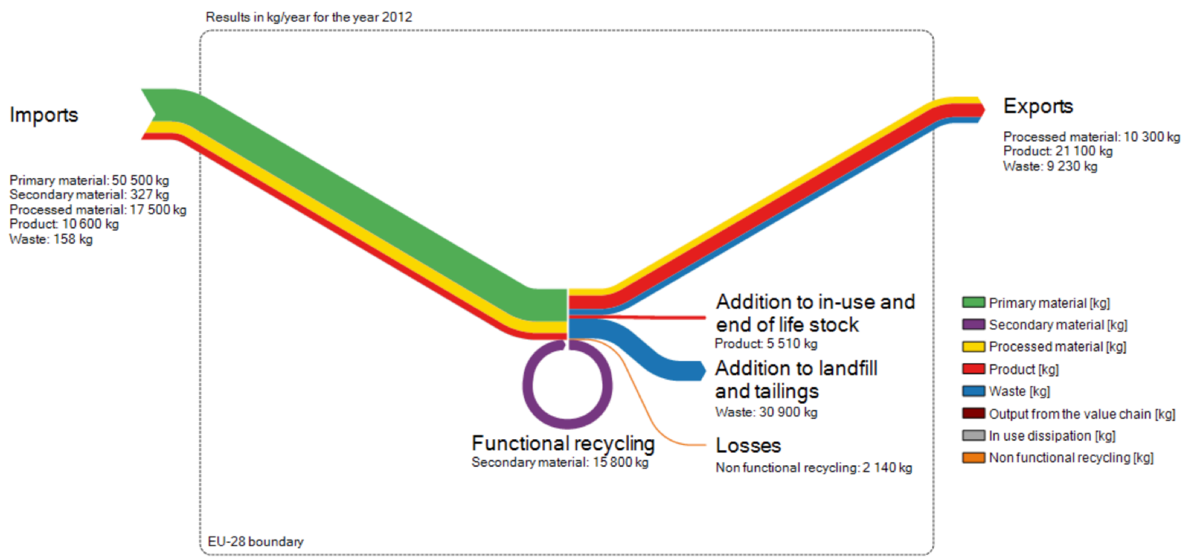


Figure 2.13 Sankey diagram for germanium flow [44]

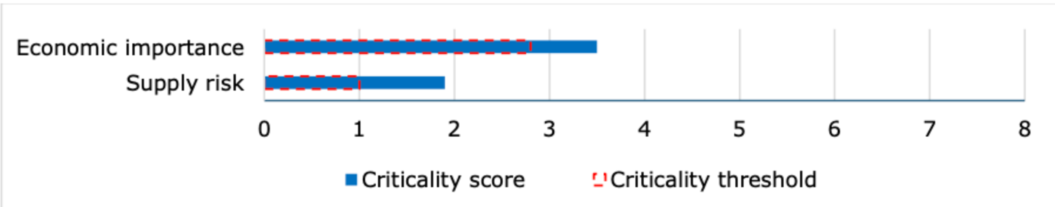


Figure 2.14 Criticality of germanium to the EU [43]

# 3 Circular economy in low-grade ore recovery

In general terms, a circular economy encourages elongating the life of raw materials in the economy, employing re-use and repair practices. Equally, it stimulates production from secondary sources through recycling [14]. However, as it was mentioned in Chapter 1, it is unrealistic to believe that these sources will be able to suffice raw material demand in a short or even in a medium-to-long term. It suggests that the mining industry—primary extraction—will continue to represent a large share of raw material supply. Unfortunately, as far as the circular economy is concerned, the extractive industries are excluded from the regenerative loops, as can be seen in Figure 3.1 [15]. In this chapter, both the CE concept and the possible actions the mining industry can partake to be included in the circular economy action plans will be further explained.

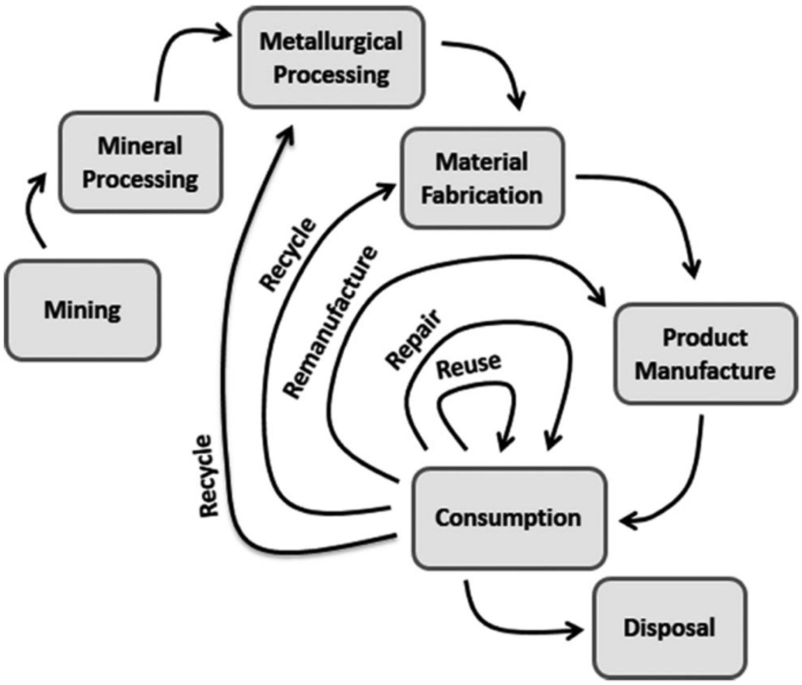


Figure 3.1 Circular economy diagram [15]

## 3.1 Circular economy concept

According to The Ellen Macarthur Foundation, the circular economy is a closed-loop economic system where products, materials, and resources keep their value for as long as possible. Therefore, waste generation is minimized. The goal of CE is to dissociate economic activity from finite resource consumption through the principles of reduction, re-use, and recycling, in other words, “3R”. At the same time, it is supported by a transition to renewable energy sources. The circular model intends to transcend beyond the ongoing “take-make-waste” or linear economy by redefining growth, building economic, natural, and social capital [58]. It is based on three principles:

- Design out waste and pollution
- Keep products and materials in use

- Regenerate natural systems

The ultimate aspiration for society is to reach sustainable development through the circular economy. Based upon this axiom, the European Commission adopted a CE action plan aimed to contribute to the EU's endeavors to develop a sustainable, low carbon, resource-efficient, and competitive economy. It is essential to point out that circular economy, if well implemented, can overcome the current impasse between economic progress and resource and energy consumption. For this reason, the CE can be accountable for several benefits. In fact, concerning raw materials, circular use, resource-efficient management through the lifecycle, and recycling can ensure the security of supply and enable energy savings. Aside from it, circular economy incentives substitution of strategic elements as a risk-reducing measure. Another vast beneficiary from CE is the environmental aspect, with lower impacts produced on the biosphere and less waste created [14]. Finally, since all aspects are intertwined, these benefits, as mentioned earlier, progressively will generate social and overall welfare. Yet, to successfully achieve these goals, a well-constructed policy framework that will prioritize sustainable (and economically viable) solutions must be established [59]. To this end, a proper circularity evaluation of products and services is paramount to obtain suitable results.

## 3.2 Share of underground in-situ low-grade ore exploitation towards a circular economy

When assessing the long-term outlook, circular economy implementation will gradually reduce the necessity to open new mines, thus, preserving virgin ore deposits. Though time, mine openings have been under criticism because of their irreversible implications to the environment. In this sense, under appropriate conditions, it is worth to continue ongoing operations (low-grade ore mining) rather than starting new ones in untouched areas. Consequently, the concept of elongating the life of the mine reflects the CE purpose by keeping the value of resources for as long as it is technically and economically possible [15].

At the moment, the demand for strategic elements keeps on growing steadily. Nonetheless, superficial, low-cost, high-grade ores are being exhausted. Simultaneously, industrial waste and EoL recycling input rates are still relatively low, particularly when compared to mining activities (Figure 3.2). In spite of the outstanding efforts currently being carried out to minimize waste, harmful consequences, and to free the industry from primary extraction (meet CE and SD objectives), the industry—and with it, the society—continues to be unquestionably reliant on mineral exploitation. With this in mind, it is clear that in the future, underground, low-grade ore mining will not only be inevitable but become the primary mineral source. Commonly, low-grade ore is the waste that remained after the economic mining activities were finished, and as such, is not a profitable operation. It produces tailings in larger quantities and finer grain size [60]. Accordingly, not only the insufficient earnings owed to the small valuable content per ton but the extra costs the company has to withstand to prevent and mitigate negative impacts make low-grade ore mining unattractive for business.

On the path of shifting from open pit to underground mining, as of yet, one can find some high-grade ores. Alas, underground mining has its drawbacks and restrictions. For instance, from the beginning, it means higher costs caused by development operations. While plenty of research has been done, there are several matters to face. It includes some restrictions, whether the depth limitations of surveying technology, the availability of tools and technology to reach and exploit high depths and environmental and safety regulations.

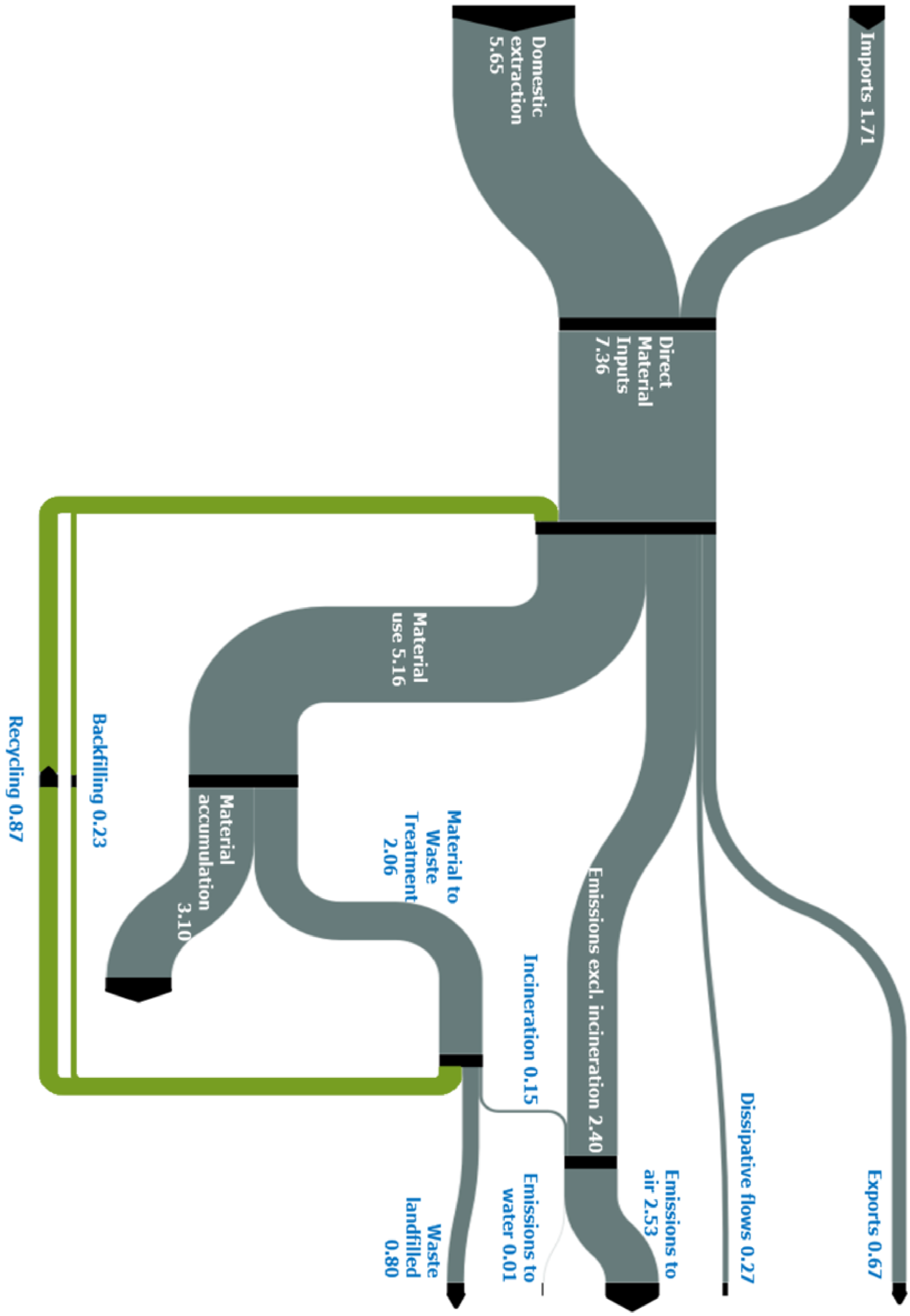


Figure 3.2 EU flows of material resources in Gt in 2016 [61]

Regardless, the mining industry can consistently strive to meet SD by dint of the circular economy concept—3R principle—in several ways. First, the reduction principle can materialize in the form of high efficiency in resource extraction. It can be accomplished through mechanization, automation, and exploit optimization overall, lowering mining dilution, hence improving the recovery of mineral processing via improvements in processing and smelting and studying other alternatives, reducing pollutants namely tailings, wastewater, etc. Secondly, re-use can be done by mine wastewater recirculation and further processing of tailings (heap and dump leaching), which is associated with additional ore recovery and lower environmental hazards. Thirdly, implementing recycling in all steps of the mining value chain [62]. Nevertheless, technical and economic aspects must be carefully considered to suitably fulfill SD goals.

With the general objective to contribute to sustainable development, there has been meaningful labor to develop new mining technologies and processes to perform primary extraction in the most eco-effective way. This initiative aims to apply circular economy principles not only as a whole but at the mine site level [15]. As a consequence, CE principles can be used to mining underground in-situ low-grade ore, by extracting in the less invasive way the target minerals while maintaining the integrity of the rock mass. In other words, waste generation could be dramatically reduced since no ore other than the necessary—development works—will be extracted. It also involves wastewater re-utilization and a significant reduction in energy use and waste/tailings generation.

# 4 In-situ bioleaching

## 4.1 Bioleaching history

Bioleaching for copper recovery was unknowingly conducted several centuries before the discovery of bacteria [63]. Bio-oxidation from sulfide ores was carried out in China, Sweden, Germany, and elsewhere. Above all, it was done in the Rio Tinto mines in south-western Spain, which are deemed to be the cradle of biohydrometallurgy [29]. Back then, it was an experimental process with no known biological connection. Despite its extensive use, *Acidithiobacillus ferrooxidans*, and its contribution of reduced sulfur and iron (III) oxidizing in producing iron (III)-containing sulfuric acid that can dissolve some sulfide minerals was not scientifically established until 1947. Since the 1950s, substantial research has been done. Then, in 1980, bacterial use for commercial activities at a large scale began in the form of the heap and dump leaching of lean-grade ores. In 1986, bioreactor processing to recover gold from sulfides was commercialized. In the years to come, stirred tank reactor systems for thermophilic bioleaching of base metals—like copper, zinc, and nickel—concentrates were settled [64].

Notwithstanding the “cleaner” characteristics of these biomining processes, and the fact that they are performed on large-scale operations, they continue to bear a minor share in the metal mining sector (approx. 15% of global copper production, 5% of gold, and fewer percentages of other metals like zinc). The principal justification for this is the low velocity of these processes when compared to pyrometallurgy. As well, in a handful of situations, biomining has failed to achieve wanted results and has been linked to environmental problems. Furthermore, it is worth mentioning that, for these biomining methods, certain energy-demanding and $CO_2$-generating activities used in regular metal mining (pyrometallurgy) are still imperative (Figure 4.1) [18].

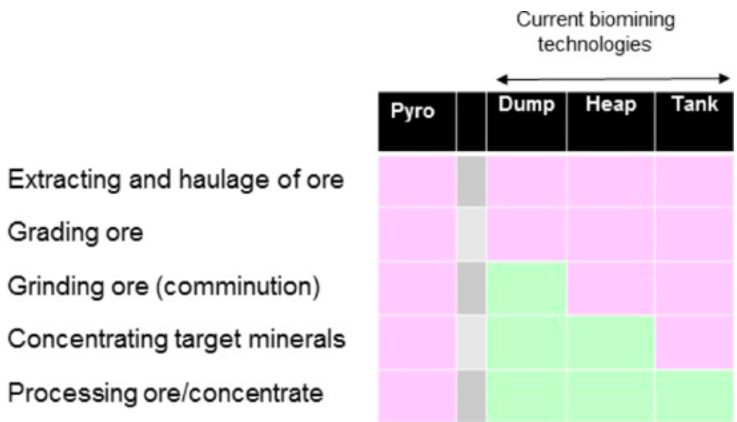


Figure 4.1 Comparison of conventional mining and biomining early stages (pink: required, green: unnecessary) [18]

On the other hand, in-situ bioleaching—with native microorganisms—was first executed in the 1960s to recover uranium and copper. Through time, it experienced a more subtle evolution than the other biomining operations, for it was destined to be implemented in hard-to-mine ores [64]. The slow pace of development of in-situ bioleaching is owed to various technical restrictions (high complexity of deposits, among others). Another possible motive is that it was seldom to find ores where extraction via in-situ bioleaching was economically viable. As a result, it was not as common as the other processes. Nonetheless, in-situ bioleaching has remarkable advantages over conventional mining and processing methods, predominantly for metal recovery from low-grade and run-of-mine ores [18]. Moreover, with the increasing number of stringent regulations, and the pursuit of sustainable development, in-situ bioleaching is gaining attention for its smaller carbon footprint. That is to say, it requires even less energy and generates less $CO_2$ than the other biomining technologies because it avoids the highly-polluting stages of recovery, as can be seen in Figure 4.2.

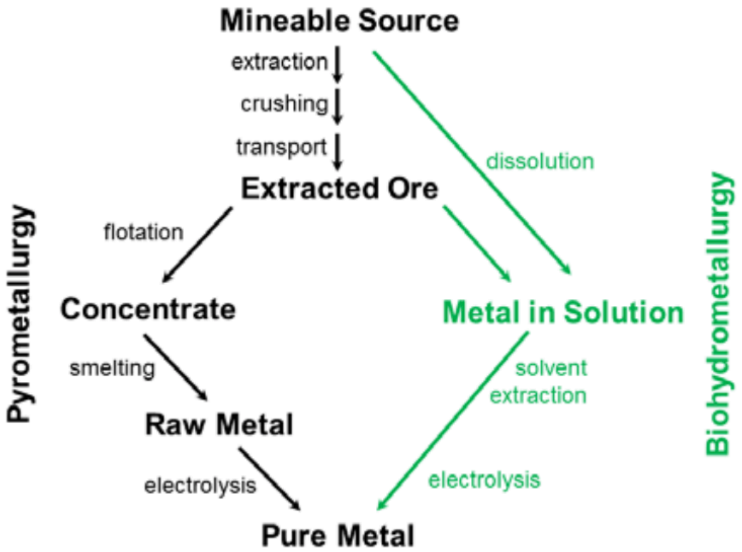

Figure 4.2 Comparison of pyrometallurgical and in-situ bio-hydrometallurgical process chains [12]

## 4.2 In-situ bioleaching process

Biohydrometallurgy is a promising interdisciplinary technology to recover valuable metals from low-grade ores. In general, bioleaching is a combination of mining and processing method defined as *"dissolution of metals from their mineral sources by certain naturally inhabiting microbes"* or the use of microorganisms to transform metal compounds so that the elements can be extracted through filtration processes from the leachate [65]. The bioleaching process uses chemical and biological reactions to dissolve insoluble metal compounds such as metal-sulfides (MeS) into a liquid solution. The products obtained from this reaction are metal ($Me^{2+}$) and sulfate ions ($SO_4^{2-}$). The core of the process is the naturally occurring iron sulfides that provide ferric iron ($Fe^{3+}$) as an oxidizer for the reaction, which then is reduced to ferrous iron ($Fe^{2+}$). The microorganisms (*Acidithiobacillus ferrooxiodans, Acidithiobacillus thiooxidans, and Leptospirillum ferrooxidans*) which are known for acid mine drainage, renovate the ferrous ions by oxidizing them again to ferric ions to close the loop (Figure 4.3) [12]. The process consists on the following steps: (1) the initial bacterial-containing solution is pumped and must percolate through the rock to dissolve the metals; (2) after the solution is fully charged with metals (pregnant solution) it is extracted from the rock; (3) the pregnant solution is further filtered to obtain the pure metals; (4) the remain bacterial-containing leachate closes the loop repeating step 1.

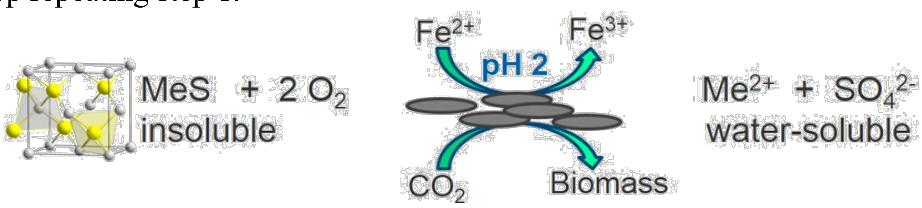

Figure 4.3 Chemical reactions in bioleaching process [66]

Applying biohydrometallurgy as an in-situ leaching technology implies that the removal of targeted metals from the mineral deposit is realized without the physical extraction of the rock. Suggesting significant financial savings resulting from:

- Lower development costs in the mine, processing plant;
- Reduction of infrastructure and energy requirements;
- Potential to start production with low capital cost followed by an increase in production, allowing the use of profits to fund mine development instead of debt financing;
- Capability of simultaneously mining several stopes; and,
- Flexibility in production capacity, which is to say, a more manageable increase of production in high-price periods and vice versa.

When speaking of environmental aspects, this method allows extraction with the slightest disturbance to the existing conditions, by not having open pits and no rock dumps and tailings to manage. Additionally, there mined volumes are smaller, reducing the surface, water, and air contamination risk. Accordingly, in-situ bioleaching can take place in the vicinities of inhabited areas and a diverse range of climates. The main environmental risk regarding this method is the loss of the liquid solution to the soil, surface water, and aquifers, which can cause water contamination and soil damage. To elude any risk, as for all mining operations, responsible planning, operating, and closure plans must be responsibly evaluated to evade hazardous situations [67]. Even though in-situ bioleaching can provide a vast amount of advantages, it is still on a testing scale. In the hope of contributing to this method's progress to reach the industrial level, in the BHMZ facilities within the Research and Educational Mine "Reiche Zeche" of the TU Bergakademie Freiberg up-scaling testing is being done. Therefore, this work aspires to identify not only the benefits but also the shortcomings of in-situ bioleaching when implemented in a case-scenario of commercial production.

## 4.3 Applicability of in-situ bioleaching

In-situ bioleaching can offer an opportunity for cost-effective exploitation of low-grade metal ore when conventional methods are not a possibility. However, as it was aforementioned, to undertake this method, individual circumstances must be fulfilled. After meticulously surveying of the mineable zone, the most critical parameters that allow in-situ bioleaching use are:

- High permeability of the mineralization and low permeability of the host rock;
- Lixiviant must favor selective leaching of the target minerals;
- Distribution and style of mineralization and absorption properties of the rock; and
- The underground physical and chemical conditions ought to enhance bacterial growth.

In the first place, permeability is the most crucial parameter of all, for it should grant a sufficient flow of lixiviant to percolate throughout the rock. Besides, it needs to let the pregnant solution to be collected for solvent extraction. Nevertheless, when permeability is not enough, conditioning methods such as blasting, hydraulic fracturing, and water pressure blasting, among others, can be performed. Hence, there will be an increase in the specific surface and a decrease in the particle size of the substrate so that microbes acquire more contact surface, resulting in more metal output. Another issue is unevenness in permeability, because it may lead to the generation of stagnant zones where the solution is lost, and non-leached zones.

Consequently, a precise investigation on where the feeding and drainage holes patterns are driven has to be assessed. The most critical issue is when the permeability of the surrounding host rock is higher than that of the mineralized area. In those cases, in-situ bioleaching no longer applies.

Secondly, ensuring selective leaching of the sought elements is essential. Dangerous consequences can occur if unwanted components are extracted. For instance, if toxic components are leached, environmental issues could emerge, or if forceful leaching of rock-forming elements happens, it can cause instability of the rock mass. Thus, thorough consideration of lixiviant, as well as acidification conditions, are vital in making the process successful. Thirdly, the position and exposure of the end minerals greatly influence the leachability. The most convenient locations for them are open pores, gaps, and fractured rocks. As for exposure, ore minerals located inside inert minerals are impossible to recover with lixiviant. Likewise, rocks with high absorption properties are unacceptable for in-situ bioleaching [67].

Finally, a set of conditions is required underground to ensure bacterial growth. In particular, oxygen is necessary since it acts as an electron acceptor for the process, and it provides energy for the acidophilic bacteria. With this in mind, $O_2$ and $CO_2$ content shall be suitable for the microorganisms to survive and to grow. In the same way, the already stated bacteria favor pH values between 2 - 3 and temperature ranges of 10 - 37 °C [16]. Lastly, other noteworthy parameters of mineralization are depth (< 150 m), morphology (tabular deposits), and distribution (Equally distributed) [67].

# 5 Framework for modeling mineral exploitation flows of mining methods

As has been noted, in-situ bioleaching has a considerable potential to assist progress towards sustainable development. It can facilitate existing mines to prolong exploitation for as long as minerals keep being recoverable at reasonable environmental consequences and financial costs. So much that, the loss of nonrenewable resources would be minimized. This mining and processing method could be seen as one of the mining industry's contributions to CE and SD objectives. With this intention, assessing in-situ bioleaching's improvements regarding circularity at the mine site level when compared to conventional methods is fundamental. So, a framework composed of a set of indicators based on Material Flow Accounting (MFA) will be implemented. The framework will reflect and measure several parameters to address different issues that commonly affect the mining industry regarding productivity, the efficiency of metal-recovery, and environmental impacts. This chapter will explain the MFA principles as well as introduce the specific indicators adapted to mining that will be evaluated.

## 5.1 Material Flow Accounting (MFA)

Material flow accounting is a standardized method to measure and analyze raw material used on a national or regional level. It provides data on consumption-based material use throughout the economy [68]. Hence, the European Statistical Office Eurostat developed a methodological guide that focuses on economy-wide material flow accounts (EW-MFA) and balances. They aim to display the economy's metabolism. More precisely, physical inputs to the economy, accumulation within it, and its outputs to the environment and other economies. Theoretically, EW-MFA and balances, and the indicators derived from them, are based on an environment-economy model, where economy/society is enclosed within the environment, and their connection is through material and energy flows (Figure 5.1). All in all, MFA and balances deliver an overview from which material flow-based indicators can be established [69].

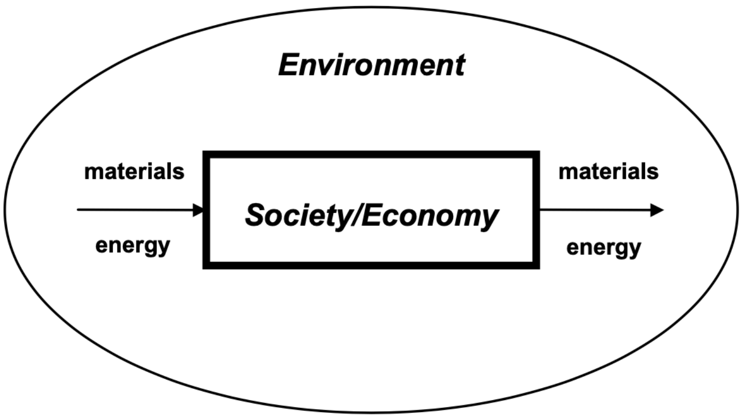


Figure 5.1 Environment-economy model [69]

It is important to recall that an indicator is a parameter—a measured property— or a value derived from a parameter that gives information on the economic, environmental, and social performance or impacts of an organization related to its material aspects. These material aspects expose the organization's most relevant impacts, which are pivotal for assessments and stakeholder's decision making [70]. The indicators obtained from MFA and balances were designed to analyze large scale economies. Nonetheless, to be able to analyze the efficiency of an industrial area, Sendra, Gabarrell, and Vicent (2007) adjusted the MFA derived indicators and complemented them with water and energy indicators [71]. Accordingly, being the mining industry, an industrial area, Lèbre, Corder, and Golev (2017) further adapted the MFA-based indicators to enable quantification on flows of ore and mineral losses to waste. The purpose of this set of indicators was to permit comparisons between mining projects to pinpoint weaknesses and so generate strategies to minimize waste losses and optimize mineral resource utilization [15].

## 5.2 Key performance indicators description

Nowadays, the mining industry is facing many challenges that are mostly driven by social and environmental expectations of welfare for future generations. Besides, the increasing number of regulations are demanding industries to improve their processes to abide by the circular economy principles so that sustainable development goals can be met. Thereby, in the effort to succeed at evaluating and quantifying the improvements provided by new mining methods, indicators are helpful. A good indicator should be representative, scientifically valid, simple, easy to interpret, give warnings on irreversible tendencies, and be based on thoroughly documented and available data [72]. In keeping with those above, this thesis will present a series of indicators based on the Eurostat methodology but tailored, taking into account the previously cited works to evaluate a mining method's performance. This analysis intends to assess the implementation of a mining method principally in terms of productivity, consumption, waste generation, overall emissions and efficiency. The proposed indicators are meant to allow two or more different mining methods to be compared when they are applied to analogous ore deposits on an industrial scale, thus, evidencing their benefits and disadvantages.

Table 5.1 Indicators to evaluate mining methods

| Indicator | Definition | Unit | Description | Relation to Lèbre et al. (2017) and Sendra et al. (2007) |
|---|---|---|---|---|
| | | **PRODUCTION** | | |
| **TP** | Total Production | t | Target element extracted in one year | Corresponding indicator is expressed in US$ in Lèbre et al. (2017) |
| **EP** | Extraction Productivity | t/h | Total mineral extracted per hour | No equivalent indicator |
| **WP** | Worker Productivity | t/worker·a | Total mineral extracted per worker | Same indicator as in Sendra et al. (2007) |
| | | **CONSUMPTION** | | |
| **TEC** | Total Energy Consumption | GJ/a | Amount of energy related to the total production | Same indicator as in Lèbre et al. (2017) and Sendra et al. (2007) |
| **ECW** | Energy Consumption per Worker | GJ/worker·a | Total amount of energy spent per worker to reach total production | Same indicator as in Sendra et al. (2007) |
| **TAC** | Total Air Consumption | t/a | Total amount of air required to reach the total production | No equivalent indicator |
| **TWI** | Total Water Input | t/a | Total amount of water required to reach the total production | Same indicator as in Lèbre et al. (2017) and Sendra et al. (2007) |

| | | | | |
|---|---|---|---|---|
| **TDW** | Total Development Works | t/a | Total material moved to access the ore | Equivalent to total material moved from Lèbre et al. (2017) and to total material requirement from Sendra et al. (2007) |
| **TMP** | Total Material Processed | t/a | Total material extracted to be processed | Same indicator as in Lèbre et al. (2017) and equivalent to direct material input from Sendra et al. (2007) |
| **TWR** | Total Water Recycled | t/a | Total water that re-entered in the recovery cycle | No equivalent indicator |
| | | **EMISSION** | | |
| **TAE** | Total Air Emissions | t/a | Total amount of $CO_2$ emissions related to the total production | No equivalent indicator |
| **TWWG** | Total Wastewater Generation | t/a | Total wastewater produced by the total production | Same indicator as in Lèbre et al. (2017) and Sendra et al. (2007) |
| **TWRG** | Total Waste Rock Generation | t/a | Total solid waste generated related to the total production | Similar to total wastes generation in Sendra et al. (2007) |
| | | **EFFICIENCY** | | |
| **WRR** | Water Recycling Ratio | % | Water consumption efficiency | No equivalent indicator |
| **EI** | Extraction Intensity | - | Amount of total material processed related to the development works | Similar to eco-intensity in Sendra et al. (2007) |
| **E-in** | Environmental Inefficiency | % | Amount of output to nature per unit of material processed | Similar to extraction inefficiency in Lèbre et al. (2017) and material inefficiency in Sendra et al. (2007) |

These indicators will be used to evaluate the performance of a mining method in one year of production. That being said, total production (TP) reflects the amount of targeted metal successfully extracted from a defined deposit—or set volume of rock—by a specific mining method. In this sense, it is the main boundary condition and exposes the profits obtained by the whole operation. It is measured in tons so that the analysis is not affected by the price volatility of minerals.

### 5.2.1 Production indicators

The production-related indicators are Total Production (TP) as it was mentioned above, Extraction Productivity (EP), and Worker Productivity (WP). EP depicts the sum of extracted elements per hour, which is helpful when comparing the execution of mining methods. For this indicator, the more significant the amount of material removed per hour, the higher the profit obtained, and therefore, the time to extract the total content of the element will be reduced. On the other hand, WP illustrates the amount of ore effectively extracted per worker per annum (WP = TMP / # of workers). This indicator is strategic for safety reasons; that is, if the number of needed workers rises, the probability of accidents will also increase. Additionally, it has economic importance because if there is a higher number of workers, the operational cost related to their salary will increase. As a whole, these indicators illustrate the main profits that will be obtained by the process.

### 5.2.2 Consumption indicators

The consumption indicators are total Energy Consumption (TEC), Energy Consumption per Worker (ECW), Total Air Consumption (TAC), Total Water Input (TWI), total development works (TDW), Total Material Processed (TMP), and Total Water Recycled (TWR), they refer to the utilities needed to reach the TP. First of all, TEC is the energy consumed by the system; it comprises the specific drilling energy required as well as the electric power supply required for the mineral extraction from the ore body, fracturing operations, haulage, magnetic separation, and flotation (if needed) until both methods reach the same stage regarding element output—either concentrate for conventional methods or metal in solution for in-situ bioleaching—. Secondly, ECW reflects the energy consumed per worker per annum. It is calculated by TEC divided by the number of workers. Thirdly, TAC is the airflow required within the mine. It results from the different equipment to be used, and the amount of personnel needed underground to carry all mining operations [73]. Fourthly, TWI is related to the separation of minerals through physical, chemical, or biological processes, transport of ore and waste in slurries, dust suppression, and any other activities that require water such as backfill operations [74]. In the fifth place, TDW refers to the amount of material that needs to be extracted to access the ore. Sixthly, TMP is the material that enters a secondary process after extraction has taken place. It is worth noting that secondary processes include crushing, milling, separation, and filtration activities to attain the TP. Lastly, TWR indicates the amount of water that is re-circulated for extraction purposes. All in all, these indicators exhibit the main costs bared by the process.

### 5.2.3 Emission indicators

The emission indicators are Total Air Emissions (TAE), Total Wastewater Generation (TWWG), and Total Waste Rock Generation (TWRG). For this work, TAE denotes the air polluting substance $CO_2$ that outcome from the mining process—if necessary, other polluting substances can be considered, such as CO, $NO_X$, and $SO_X$—, which are produced by the machinery and quantity of explosives used. Secondly, TWWG is related to the water used in ore extraction and processing activities, which cannot re-circulate into the process. In the last place, TWRG refers to the solid waste generated mainly from development works. Consequently, these indicators display the primary environmentally hazardous wastes caused by mining.

### 5.2.4 Efficiency indicators

Regarding the efficiency indicators, these are Water Recycling Ratio (WRR), Extraction Intensity (EI), and environmental inefficiency (E-in). Initially, WRR is the water consumption efficiency; it represents the percentage of water that is recycled throughout the process with respect to the TWI (WRR = TWR / TWI·100%). Secondly, since development works are done in the most optimal way to extract the ore, EI symbolizes the relationship between the amount of material extracted to obtain the TP and the development needed (EI = TMP / TDW). This indicator is helpful when comparing mining methods while considering economic reasons related to development works. That is, the higher amount of material extracted per ton of development, the less cost incurred and greater the profit achieved. Thirdly, E-in portraits the environmental consequences of mining, by linking the waste generated to the TP [E-in = (TAE + TWWG + TWRG) / TP]. In summary, these indicators present an overview of the main benefits that a mining process can provide.

# 6 Case of study: In-situ bioleaching on Reiche Zeche mine

Reiche Zeche is a mine situated in the city of Freiberg, in the region of Saxony, Germany. Moreover, mining in this region started in 1168, when silver-bearing galena (PbS) was discovered. The Freiberg deposit is a lead-zinc deposit formed in hydrothermal veins within the already existing gneiss. The vein sets have different strike directions, which are roughly N-S and W-E, with a length along the strike of several hundred meters. These ore veins have an average thickness of 20 – 40 cm. Regarding inclination, most of the ore veins have a dipping angle between 40° and 60°. The chief minerals found in this deposit are galena, sphalerite (ZnS), pyrite ($FeS_2$), chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS) and quartz ($SiO_2$) [75]. Within the stated minerals, sphalerite comes of great importance, for it contains indium with an average grade of 40 parts per million (ppm), which is the target element for this study [76].

## 6.1 Mine test-site position

The test-site is located at the Wilhelm Stehender Nord ore vein. The ore body block was chosen based on its integrity and proper mineralization to address in the best possible way the bioleaching extraction. The distribution of ore inside the block was carefully assessed through geophysical methods, such as seismic survey and geoelectrical borehole tomography. As it can be seen in Figure 6.1, the seismic velocity within the ore block fluctuates between 4,400 m/s (blue) and 6,900 m/s (red). It enlightens the significant mineralogical changes as well as the homogeneity of the rock mass. The red regions represent high wave velocity, which means high mineralization and weathering of the ore body, whereas blue areas generally denote gneiss—hence, less mineralization—. Consequently, the ideal test-site requires enough mineralization, considerable homogeneity, and integrity of the rock. These characteristics are met in sections where the wave velocity is 5,000 – 6,000 m/s (green and yellow) [12].

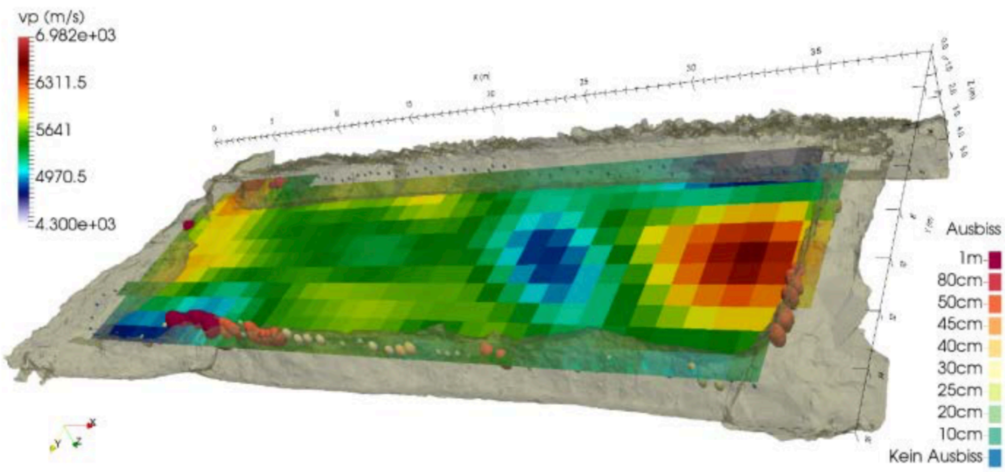


Figure 6.1 Seismic model of ore body block [12]

## 6.2 Mine test-site design

The stope chosen is located in a depth of 150 m. It has a thickness that varies from a few cm up to 1 m and a dipping angle of 50°. The block has a length of 35 m and a height of 10 m in dip direction, as seen in Figure 6.2. Raises surround the stope at both sides, and the access is through the head and bottom road, which have a cross-section of approx. 6 and 5 $m^2$, respectively. The boreholes were drilled from the head road with a diameter of 53 mm and a spacing of 20 – 50 cm. The grid consists of drainage (red) alternated with feeding boreholes (green). Accordingly, to Figure 6.2, the drainage holes were drilled the entire height of the stope to allow the leaching solution to leave the block. In contrast, the feeding holes have a length of 6 m to keep a rock pillar that will act as a natural seal and will prevent leakage of the solution to the bottom road [12].

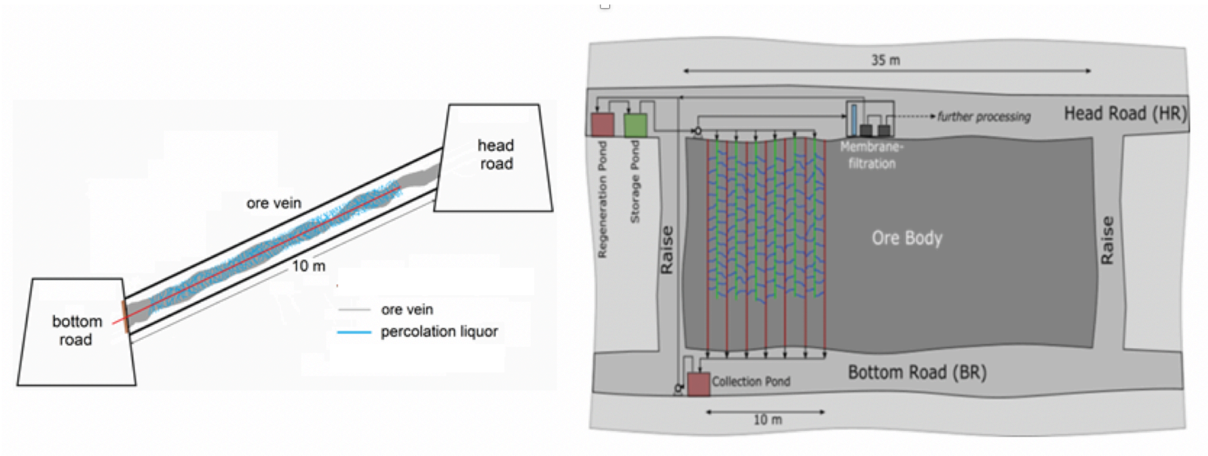


Figure 6.2 Test-site scheme within the stope [12, 16]

Additionally, the stope's permeability must be increased to ensure suitable streaming paths for the leaching solution throughout the rock. So, different fracturing technologies were attempted, among them are pre-conditioning by conventional blasting with detonating cord, hydraulic fracturing (Figure 6.3 left) and Water Pressure Blasting (WPB) (Figure 6.3 right). The first one proved not to be useful because even though it generated cracks in all directions—increasing specific surface—, it damaged the structural integrity of the boreholes, leading to the uncontrolled flow of the solution. The second approach was not the most favorable either since it generated few cracks which were narrow and could close quickly—hence, not enough specific surface was created—, and as a consequence, there was no uniform permeability increase. Consequently, the third approach, WPB, demonstrated to be the most beneficial. It consists of boreholes filled with water, which are sealed with a detonating chord inside, creating an even hydrostatic pressure inside the hole. When the cord is ignited, the water acts as propagation media, which results in even radial and circumferential distribution of cracks, causing a sufficient specific surface for leaching purposes [16].

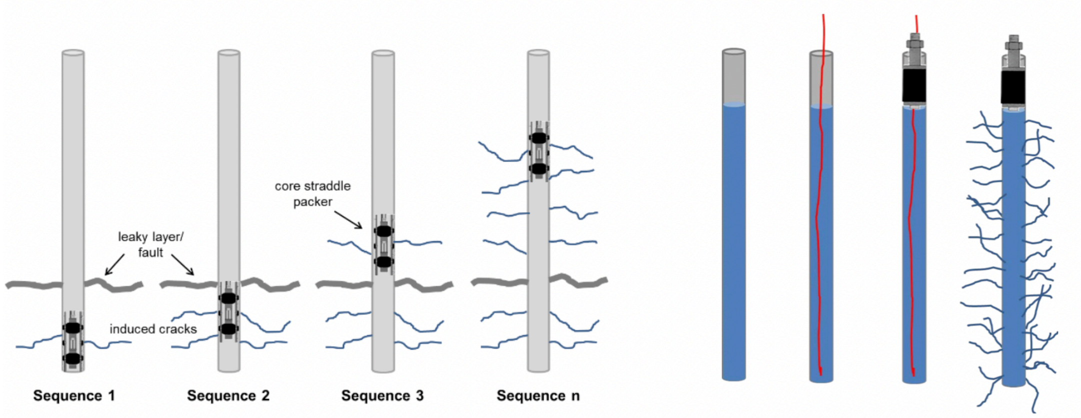


Figure 6.3 Hydraulic fracturing (left) and water pressure blasting (right) [12]

## 6.3 Bioleaching process

The chemical process, as well as the microorganisms used, were already explained in Chapter 4.2. For the test-site, the bacteria were originated and collected at the mine. Then, they were cultured and oxygenated in a storage pond. Once there were enough bacteria, the solution was pumped through the feeding boreholes to allow it to flow within the induced cracks. After a given time, the pregnant solution is gathered in the drainage holes and guided to the collection pond that is located on the bottom road. It is important to note that the pressure regulators allow controlling the dwell time in every borehole. Subsequently, the pregnant solution is pumped back to the storage pond in the head road to close the cycle. Finally, when there is sufficient metal content in the pregnant solution, it is pumped to the following processing step, which is the membrane filtration plant (Figure 6.2).

# 7 In-situ bioleaching feasibility assessment by means of MFA indicators

Albeit in-situ bioleaching testing at Reiche Zeche mine is still on a small scale, it has proven to be promising for upscaling. With this in mind, the analysis will be done based on a real-life size deposit and the conditions previously mentioned in Chapter 6, to be able to use the data obtained from the test-site. Therefore, a theoretical mine design will be made and compared to a conventional design to analyze the possible benefits and shortcomings of the in-situ bioleaching operation. For this work, all indicators will be calculated for production activities; that is to say, all the activities carried out to achieve the metal in solution in the case of in-situ bioleaching and the concentrate in the conventional mine design (Figure 4.2).

Moreover, the following assumptions were made grounded on the Reiche Zeche deposit. The deposit studied is a gneiss-hosted lead-zinc sulfide deposit with low water inflows. Mining activities started with the surface—open pit-—operations. Nonetheless, the evaluated deposit is only concerned with the succeeding underground development of the mine, which comprehends a depth from 118 – 400 m. Both host rock and ore body are competent rock, with RMR values of 80 – 100 and 60 – 80, respectively. Even though the rock is competent, permanent structures will be supported with a combination of split set anchors and shotcrete.

In contrast, temporary structures like drilling drifts will be supported with split set anchors and wire mesh. For drilling activities, the specific drilling energy for the rock type was considered to be 253 kWh/m$^3$ of rock [77]. The target element to be extracted is Indium, which is distributed among the ore with a uniform grade of 0.0041%. The ore body has a yearly average temperature of 12°, a dipping angle of 50° and a uniform thickness of 12.58 m. The dimension along strike is 1,030 m, and along the dip is 370 m. Assuming a specific gravity (S.G.) of 2.8, the possible ore to be extracted is 13,423,866 t. Considering the grade declared, 550.4 t of Indium can be recovered from the ore body. For ventilation calculations, the required amount of air per second is calculated based on the number of people underground with a value of two m$^3$/min, and the diesel-powered equipment, being four m$^3$/min·kW. Analogously, the air emissions were estimated based on the explosives used (Ammonium Nitrate Fuel Oil - ANFO) with a value of 0.19 $tCO_2/t_{ANFO}$, and diesel-engine vehicles, which have an average of 35% efficiency [78], a low heating value of 36 MJ/L [79] and generate an average of 2.66 $kgCO_2/L$ [80]. Finally, regarding the time of mining activities, the amount of working days per year that will be assumed is 336, having three shifts per day, and 8-hour shifts [81]. In summary, this chapter will explain all the calculations made to obtain the key performance indicators for each of the theoretical designs, in light of the assumptions mentioned earlier.

## 7.1 Conventional mine design

The conventional mine design was developed by Louis Schaarschmidt [81] and here adapted to the boundary conditions stated earlier. The method chosen was longitudinal, descending long-hole stoping with cemented backfill. The access to the ore was via a decline placed in the middle of the ore body, generating two wings, one to each side with a length of 500 m. Hauling was made through the decline with trucks. The vertical spacing between levels was chosen to be 44 m. So, the dimension of the stopes in dip direction is 60 m, and accordingly, the number of levels inside the mine is six (Figure 7.1). The length of the stopes is 60 m as well, based on the literature review, and 10 m rib pillars were left in place for stability reasons, which result in 14 stopes per level for a total of 90 stopes in the mine (Figure 7.2).

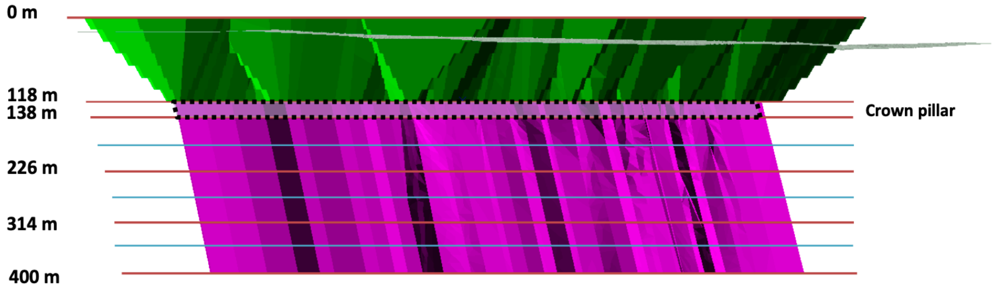


Figure 7.1 Front view of general layout Conventional Method [81]

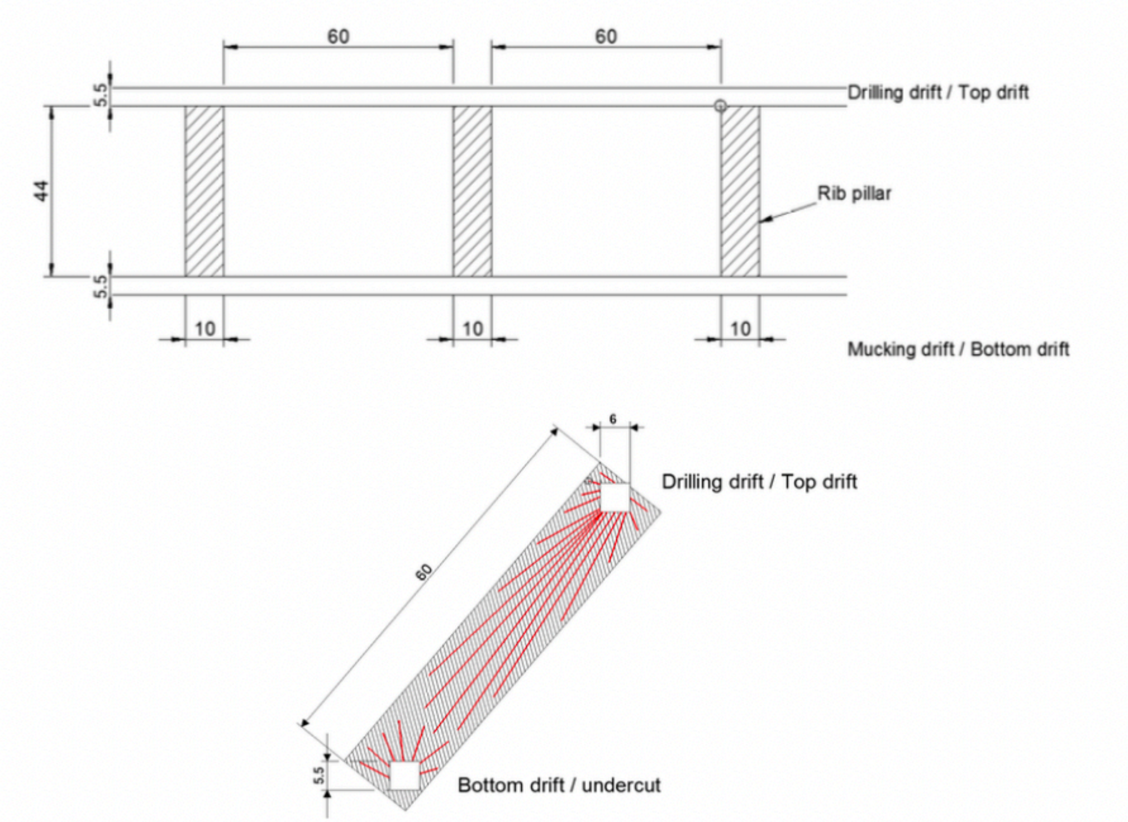


Figure 7.2 Stope dimensions and drilling scheme (m) - Conventional Method [81]

The mining sequence consists of the stopes being drilled from the top part via drilling drifts, loaded with ANFO, and blasted. The blasted ore falls into the five draw-points placed in the bottom of the stope, where remote-controlled LHDs muck it and trucks further haul it. When the stope has been entirely extracted, cemented backfill—composed by crushed ore, tailings, cement, water, and sand—is pumped into the void left by the stope, and it is left to curate. Once the backfill has reached its desired strength, the rib pillars are extracted to maximize production. To perform all the conventional mining operations, the number of workers needed is 73, being 25 workers for the first shift and 24 for the second and third. Finally, regarding ventilation measures, a fan was located on the decline to drive fresh air inside the mine. The air will flow through the extraction points and will then leave via the ventilation boreholes drilled at both ends of the ore body (Figure 7.3). For more information regarding this design please refer to the original work.

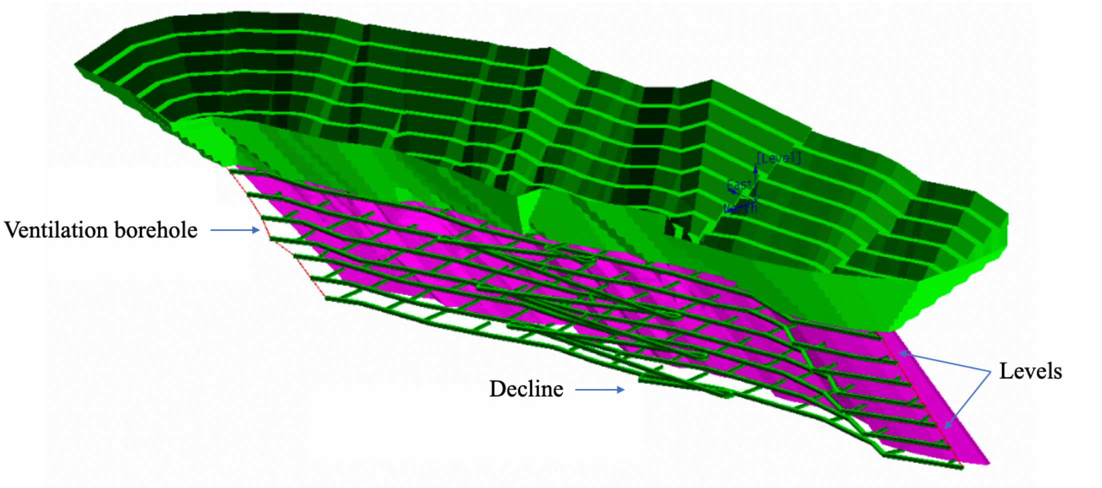


Figure 7.3 General layout Conventional Mining Design [81]

### 7.1.1 Production indicators

The annual run of mine (ROM) objective for this design was to extract 1.5 Mt of ore. However, considering a dilution of 15% and the fact that about 68% of the extracted material is valuable after passing through the processing plant; according to Dr.-Ing. George Barakos, the TP for this method is 42 t, which implies that the life of the project until all Indium is extracted is 7,8 years.

Additionally, the EP is related to the ore extracted from the mine. For this reason, to achieve the ROM, the actual amount that has to be mined is 1.7 Mt due to dilution. As a consequence, the extraction productivity is 214 t/h. Finally, the WP calculation is based on the ore mined and the number of workers; therefore, worker productivity is 23,630 t.

### 7.1.2 Consumption indicators

The TEC is related to the electrical power supplied to reach the concentrate of Indium. It is the sum of the highest energy consumption activities, such as the specific drilling energy which is 454,807 GJ/a; the energy requirement for ventilation activities, 9,934 GJ/a, and the processing activities required—crushing and sorting, milling, regrinding, magnetic separation, flotation, and utilities—, accountable for 170,101 GJ/a. Then, the total energy consumption is 634,842 GJ/a. In the same way, the ECW equivalent is 8,696 GJ/worker·a.

The TAC is calculated based on the number of workers and vehicles in the mine. The vehicles required for transportation of personnel were in total 2 Toyota Landcruiser Prado for the foreman and the engineer, while for electricians and locksmith teams, 5 Toyota Hilux were considered. For extraction and development activities, two LHDs (Caterpillar R2900G, R1300G), respectively, were chosen. The drilling activities demanded one long-hole production drill (Sandvik DU421) and one jumbo drill for development (Sandvik DD422iE – electrically powered). The total amount of trucks estimated was seven (Bell B45E), where six of them will be used to haul the ore from the draw points to the processing plant, while the other truck will be used for development and waste rock haulage. For rock support operations, one rock bolting drill (Sandvik DS311) was selected. For safety reasons, one truck to carry the explosives (MAN D0834) is needed as well. Finally, a raise bore unit (Robbins 73RM) is necessary to create the ventilation boreholes. Under such circumstances, the air requirement was calculated to be 95.8

$m^3/s$, which represents a total air consumption of 3,359,693 t/a. This calculation was conducted for 365 days of the year because ventilation is vital for the safety of the workers underground.

The TWI is associated with the groundwater supply needed to fulfill the requirements of the processing plant, that are 1,000,000 t/a, the backfill operation demand, 158,412 t/a, and the dust control operations, which are highly important for this type of mining method, with a value of 3,360 t/a. Consequently, the total water input is 1,161,772 t/a.

The TDW is the volume of rock either ore or waste that must be removed to access the ore. Hence, for this method, the development works that were undertaken comprise one decline, being 249,569 t; 12 footwall drifts, with 611,520 t; 12 drilling drifts, accountable for 554,400 t; 420 draw-points, 5 per stope, generating 476,280 t; 84 crosscuts, producing 95,256 t, and 2 ventilation boreholes, with 1,308 t to be removed. As a result, the total amount of development works is equal to 255,506 t/a.

The TMP is the material that was extracted from the ore body for additional processing; it consists of the ROM material considering the dilution, which leads to a total of 1,725,000 t/a. Lastly, TWR was calculated based on the only process that recycles water, which is the processing plant, which recycles 66% of the water [81]. Thus, the total of water recycled is 660,606 t/a.

### 7.1.3 Emission indicators

The TAE for this project was estimated based on the vehicles and explosives used to reach the TP. The vehicles previously stated generate 8,738 $tCO_2$/a. Regarding explosives used, considering the daily production to be 5134 t/day, the total amount of explosives needed cause 163 $tCO_2$/a. Hence, overall, the total air emissions are 8,901 $tCO_2$/a.

The TWWG is the water either that has an inferior quality and is not worth to recycle or is lost in the process. This value comprehends the water used for backfilling operations, dust control and the percentage of process water that was not recycled in the plant. The total of wastewater generated is then 501,166 t/a.

The TWRG was calculated mainly considering the development works that generate waste, which refers to all development works except for the drilling drifts, for they are drilled inside the stope, and consequently are ore rather than waste. So, the total waste rock generation is equal to 184,264 t/a.

### 7.1.4 Efficiency indicators

The WRR reflects the efficiency in terms of water consumption, and as such, the water recycling ratio for the overall conventional mining operation is 57%.

The EI is 7; in this way, this indicator suggests that in one year, for 1 t of development material extracted, 7 t of ore was mined and processed.

Last but not least, there is E-in, that considers the aforesaid emission indicators related to the total material processed, resulting in a value of 40%. The latter implies that the total emissions are equivalent to almost half of the material extracted.

## 7.2 In-situ bioleaching mine design

The in-situ bioleaching design took place based on the assumptions made and the conventional mine design, mainly referring to the development plan, and type of machinery chosen. Nevertheless, the design was completed to comply with the different requirements of this innovative method. That being said, the access to the ore was via a decline placed in the middle of the ore body, generating two wings, one to each side with a length of 500 m. Hauling was chosen to be through pipeline boreholes, they host the pipeline system that brings the leaching agent to the stopes, and pregnant solution to the surface for further processing. Since the stope is not extracted, the potential stability problems are reduced, and for that reason, the vertical spacing between levels was chosen to be 92 m. So, the dimension of the stopes in dip direction is 120 m, and accordingly, the number of levels inside the mine is three. The length of the stopes is 125 m, and as it was mentioned earlier, no stability pillars are needed (Figure 7.4). Each stope has alternated 14 feeding and 15 drainage borehole rows, where the boreholes have an equidistant spacing of 60 cm, and a diameter of 53 mm. While the drainage holes are drilled the whole height of the stope, for the feeding holes, a pillar of 5 m is required on the bottom part of the stope to avoid solution leakage (Figure 7.5 and Figure 7.6).

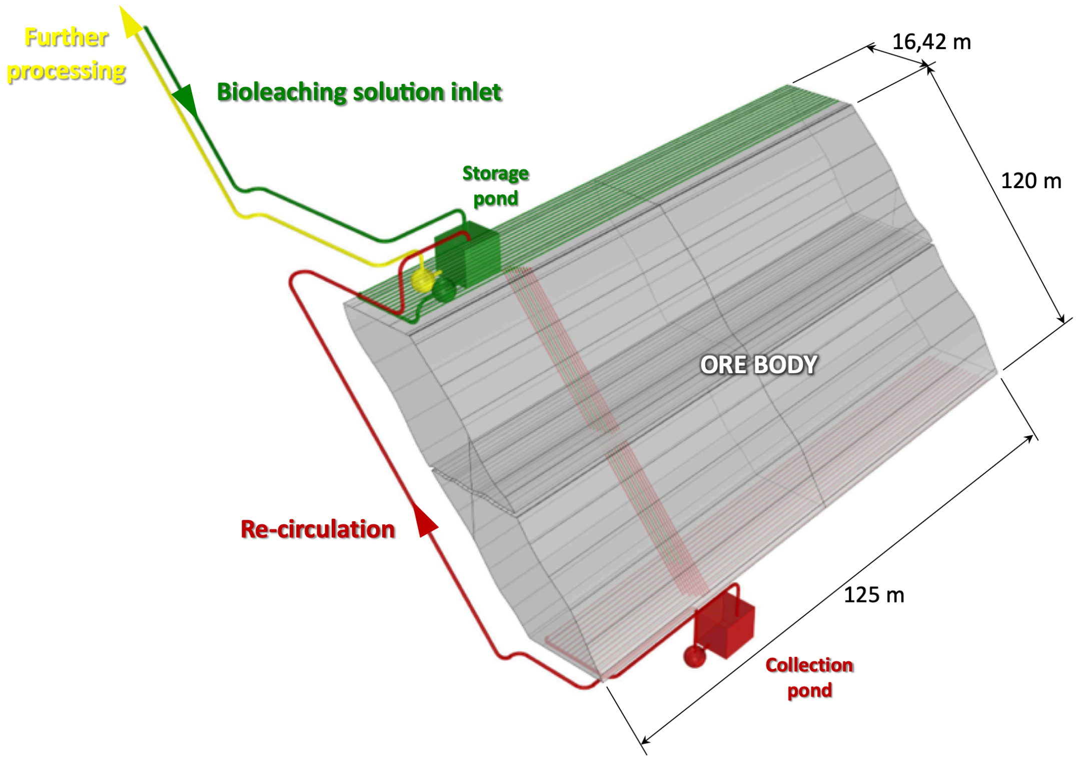


Figure 7.4 In-situ bioleaching stope scheme with dimensions

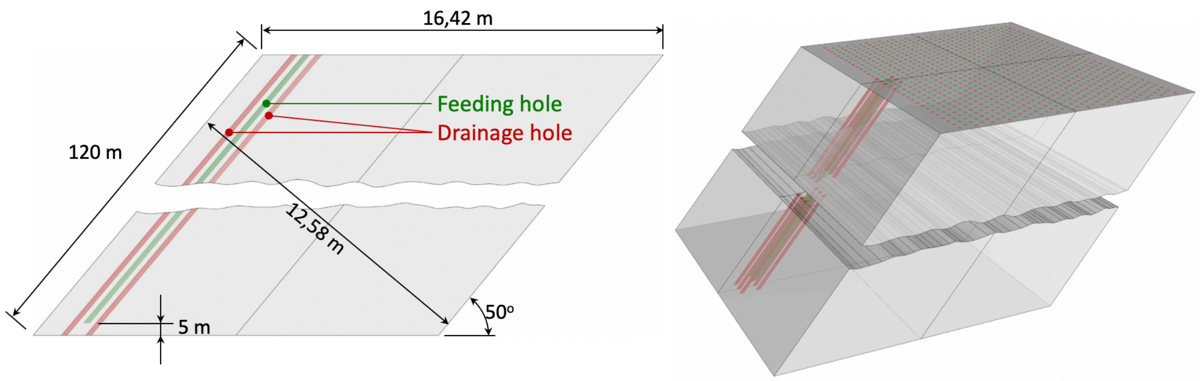


Figure 7.5 In-situ bioleaching stope – lateral and 3D view

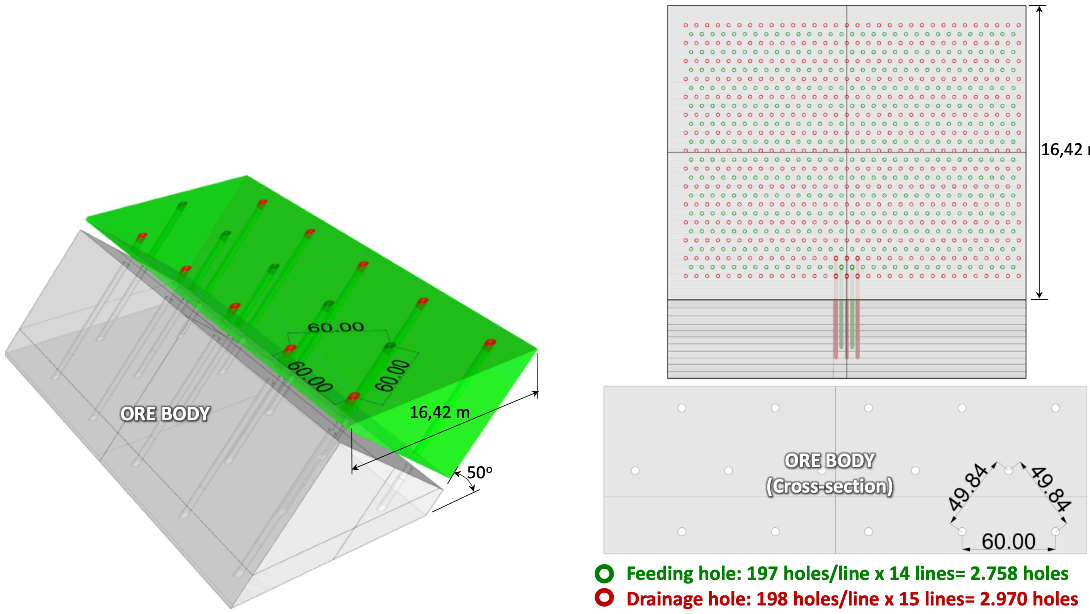

Figure 7.6 In-situ bioleaching - boreholes distribution

The flow of leaching solution per borehole was estimated to be 26,83 L/h to provide enough time to the microorganisms to perform the chemical reaction within the ore. According to section 6.2, water pressure blasting was considered as a permeability enhancement technology. The complete layout consists of 8 stopes per level for a total of 24 stopes in the mine, which for this analysis will work simultaneously throughout the year (Figure 7.7).

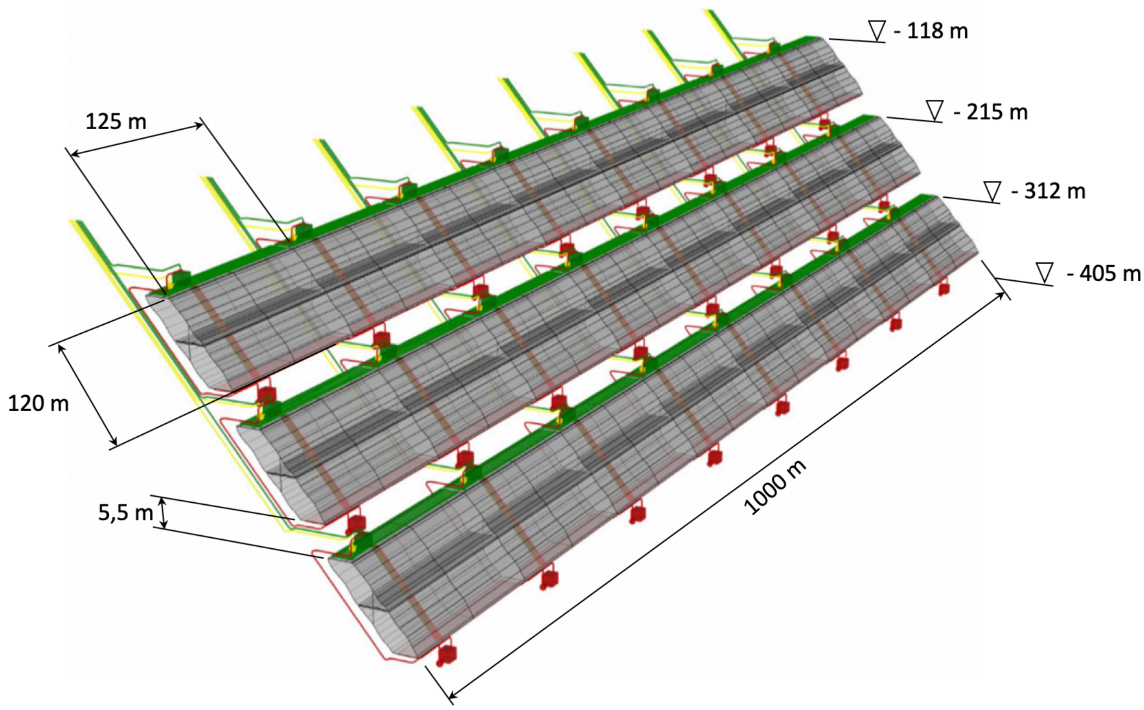

Figure 7.7 General layout of in-situ bioleaching mine design

The mining sequence was determined according to Chapter 6. It consists of drilling the stopes with parallel boreholes; the bioleaching solution that is cultivated in the surface fills all the stopes due to gravitational forces. Subsequently, with the help of a feeding pump located at the top (green - Figure 7.8), the bioleaching solution is evenly distributed within the stope, while the drainage pump (red - Figure 7.9) returns the collected solution to the storage pond. The cycle is repeated several times until the pregnant solution reaches a sufficient level of mineral content to go to the filtration process; then, the output pump (yellow - Figure 7.8) drives the pregnant solution to the membrane filtration plant placed on the surface for additional processing. Since the production activities to be executed by the workers are significantly reduced, the number of workers needed is 22, being eight workers for the first shift and 7 for the second and third. Finally, regarding ventilation measures, a fan was located on the decline to drive fresh air inside the mine. The air will flow through the extraction points and will then leave via the ventilation boreholes drilled at both ends of the ore body and the pipeline boreholes.

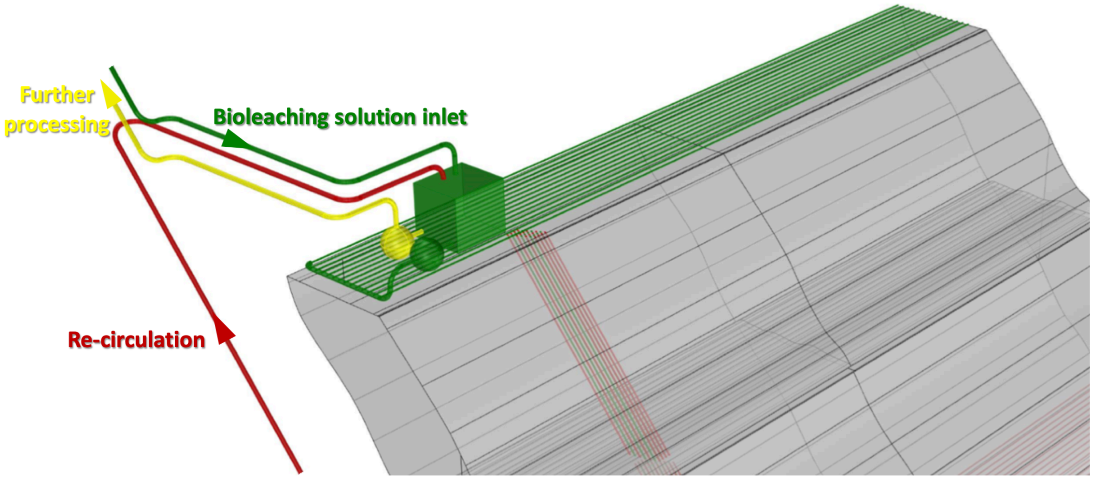

Figure 7.8 Feeding and output system close-up

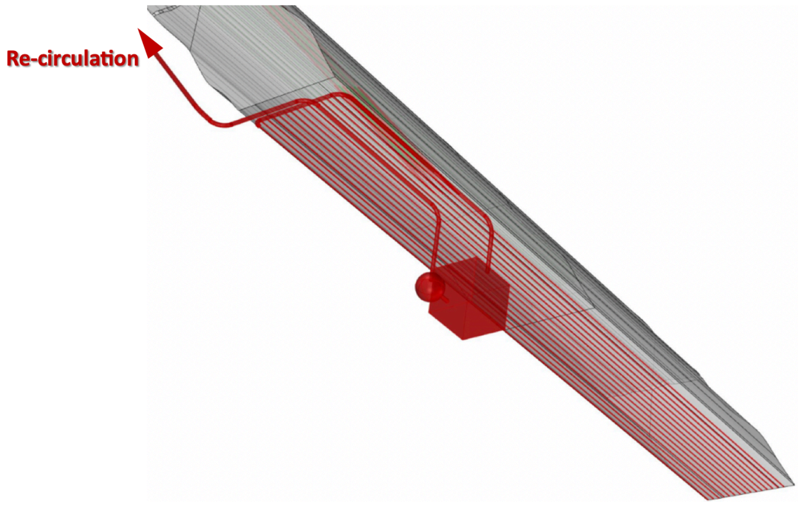

Figure 7.9 Re-circulation system close-up

### 7.2.1 Production indicators

Considering that the necessary flow of bioleaching solution per stope is 596,787,072 L/a and taking into account that the annual recovery rate estimated in the test-site for indium is $6.57 \times 10^{-7}$ kg/L. The TP for the complete mine using this method is 9.4 t, which implies that the life of the project until all In is extracted is 58 years.

For the EP estimation, it is worth mentioning that the microorganisms used in this method are not exclusively selective for indium. Still, they extract several elements, such as zinc, copper, germanium, etc. For this reason, the actual amount mined is 1.2 Mt, which comprises all the other elements extracted as well. As a consequence, the extraction productivity is 150 t/h. Finally, the WP calculation is based on the ore mined and the number of workers; therefore, worker productivity is 54,940 t.

### 7.2.2 Consumption indicators

The TEC is related to the electrical power supplied to reach the Indium in solution. It is the sum of the highest energy consumption activities, such as the specific drilling energy which is 64,456 GJ/a; the energy requirement for ventilation activities, 3,469 GJ/a, and the pumps required for the hydraulic distribution of the leaching solution—input, re-circulation, and output—, that are accountable for 34,488 GJ/a. It is essential to clarify that the required power of the outlet pumps depends on the depth at which they are placed, so there are three different types of output pumps. Then, the total energy consumption is 102,413 GJ/a. In the same way, the ECW equivalent is 4,655 GJ/worker·a.

The TAC is calculated based on the number of workers and vehicles in the mine. The vehicles required for transportation of personnel were in total two Toyota Landcruiser Prado for the foreman and the engineer, while for electricians, monitoring and locksmith teams, two Toyota Hilux were considered. Since there is no extraction of material, for development mucking activities, one LHD (Caterpillar R1300G) was chosen. The drilling activities demanded one long-hole drill (Diamec 232) and one jumbo drill for development (Sandvik DD422iE – electrically powered). It was estimated one truck (Bell B45E) that is needed for development rock and waste rock haulage. For rock support operations, one rock bolting drill (Sandvik DS311) was selected. For safety reasons, one truck to carry the explosives (MAN D0834) is needed as well. Finally, a raise bore unit (Robbins 73RM) is necessary to create the ventilation boreholes. Under such circumstances, the air requirement was calculated to be 32.5 $m^3/s$, which represents a total air consumption of 1,141,348 t/a. This calculation was conducted for 365 days of the year because ventilation is vital for the safety of the workers underground.

The TWI is associated with the water supply needed to fulfill the requirements of the hydraulic system, which comprises the complete volume of solution required and the storage and drainage tanks of each stope. Consequently, the total water input is 30,519 t/a.

The TDW is the volume of rock either ore or waste that must be removed to access the ore. Hence, for this method, the development works that were undertaken comprise one decline, being 259,664 t; 6 footwall drifts, with 305,968 t; 6 drilling drifts, accountable for 1,090,401 t; 6 crosscuts, two per level, producing 6,804 t; 2 ventilation boreholes, with 1,308 t to be removed; 66,192 feeding boreholes, that are 47,022 t, and 71,280 drainage boreholes, having 52,838 t in all 24 stopes. Finally, eight pipeline boreholes were drilled as well, one per each column of three stopes, generating 14,646 t. As a result, the total amount of development works is equal to 30,392 t/a.

The TMP is the material extracted from the ore body for additional processing; it consists of the sum of all elements extracted together with the Indium, which leads is in total 1,208,676 t/a. Lastly, TWR was calculated based on the recycling rate of water for the in-situ bioleaching tests performed at Reiche Zeche mine; it is about 80%—according to Dipl.- Ing. Tobias Krichler—. Thus, the total of water recycled is 24,415 t/a.

### 7.2.3 Emission indicators

The TAE for this project was estimated based on the vehicles used to reach the TP since no explosives are required. Hence, the total air emissions are 2,601 $tCO_2$/a.

The TWWG is the water that either has an inferior quality and is not worth to recycle or is lost in the process. The total of wastewater generated is then 6,104 t/a.

The TWRG was calculated mainly considering the development works that generate waste, which refers to all development works except for the drilling drifts, for they are drilled inside the stope, and consequently are ore rather than waste. So, the total waste rock generation is equal to 10,042 t/a.

### 7.2.4 Efficiency indicators

The WRR reflects the efficiency in terms of water consumption, and as such, the water recycling ratio for the overall conventional mining operation is 80%.

The EI is 40; in this way, this indicator suggests that in one year, for 1 t of development material extracted, 40 t of ore was mined and processed.

Last but not least, there is E-in, that considers the aforesaid emission indicators related to the total material processed, resulting in a value of 1.6%. The latter implies that the total emissions are minimal compared to the material extracted.

## 7.3 Discussion of the results

The MFA-based key performance indicators were calculated to allow two different mining methods to be compared and the results are illustrated in Table 7.1.

Table 7.1 Calculation of key performance indicators

| Indicator | Definition | Unit | Conventional Method | In-situ Bioleaching Method |
|---|---|---|---|---|
| **PRODUCTION** | | | | |
| **TP** | Total production | t | 41.8 | 9.4 |
| **EP** | Extraction productivity | t/h | 214 | 150 |
| **WP** | Worker productivity | t/worker·a | 23,630 | 54,940 |
| **CONSUMPTION** | | | | |
| **TEC** | Total energy consumption | GJ/a | 634,842 | 102,413 |
| **ECW** | Energy consumption per worker | GJ/worker·a | 8,696 | 4,655 |
| **TAC** | Total air consumption | t/a | 3,359,693 | 1,141,348 |
| **TWI** | Total water input | t/a | 1,161,772 | 30,519 |

| | | | | |
|---|---|---|---|---|
| **TDW** | Total development works | t/a | 255,506 | 30,392 |
| **TMP** | Total material processed | t/a | 1,725,000 | 1,208,676 |
| **TWR** | Total water recycled | t/a | 660,606 | 24,415 |
| | | **EMISSION** | | |
| **TAE** | Total Air Emissions | t/a | 8,901 | 2,601 |
| **TWWG** | Total wastewater generation | t/a | 501,166 | 6,104 |
| **TWRG** | Total waste rock generation | t/a | 184,264 | 10,042 |
| | | **EFFICIENCY** | | |
| **WRR** | Water Recycling Ratio | % | 57 | 80 |
| **EI** | Extraction Intensity | - | 7 | 40 |
| **E-in** | Environmental inefficiency | % | 40 | 1.6 |

Both of the methods analyzed in this work have advantages and weaknesses when they are compared against each other. In general, leaching methods are known to be slower than conventional methods, since their productivity depends on the flow of the lixiviant passing through the ore. As a consequence, traditional methods have a higher extraction efficiency, as is reflected in the overall production (TP). The conventional method surpasses in-situ bioleaching notably, having an annual Indium production more than four times higher. This more significant production carries other implications; for instance, it reduces the life of the project; in this case, the life of the project was reduced by almost 87% of the time. Likewise, when considering extraction productivity, the conventional method shows to be better. However, the EP is not widely superior; it is only 30% higher in the traditional activity, which means that the most considerable difference is in the processing operations executed after extraction from the ore body. For this indicator is important to clarify that the “extraction” results in two different outputs for each one of the methods, for conventional mining is still ore, whereas for in-situ bioleaching is elements in solution. Additionally, even though the ore extracted is more abundant in the traditional method, as the number of workers needed when using in-situ bioleaching is reduced by 70%, the worker productivity is 43 % higher for this method. The reason for this is that there is no longer a need for operators for hauling, backfill, production drill, blasting, etc.

When practicing mining activities, it is vital to balance the expenditures related to the benefits obtained; that is, the mandatory energy and natural resources consumption to achieve total production. On the one hand, considering energy, the overall use for in-situ bioleaching is 84% less with respect to conventional mining. The main reason for this substantial reduction is that in-situ bioleaching is a combination of mining and processing. As such, it can avoid several high-energy stages that are compulsory for traditional methods, for instance, crushing, sorting, and milling activities. Correspondingly, the energy consumption per worker is lessened by 46%.

On the other hand, contemplating natural resources, the total air consumption was reduced by 66% for the in-situ bioleaching operations. This reduction was caused by not only the reduction in workers but also the machinery needed within the mine. Moreover, the most notable change was seen in the water input, for in-situ bioleaching needs only 3% of what is required for conventional methods. The latter, since most of the water is recycled, and it does not require backfill and dust control operations. When speaking of rock removal, the development works decrease as well. That is seen in the general layout of both methods (Figure 7.3 and Figure 7.7). While the conventional concept considers 14 stopes per level and six levels, in-situ bioleaching contemplates eight stopes per level and only three levels.

Similarly, the total material processed for in-situ bioleaching is 30% less than that for the conventional method. Exemplifying the lower effectiveness of in-situ bioleaching, for it processes 70% of the material extracted in traditional mining, yet it only produces 23% of the targeted element. Finally, the amount of water recycled in each method varies immensely, being reduced by 96% for in-situ bioleaching. This indicator is closely related to the TWI. In the conventional operation, much water is lost in the process—backfill and dust control—, and another substantial amount of water is costly to regenerate for its continuous use.

Conversely, the water is used in in-situ bioleaching to carry the microbes so that they extract the wanted elements. Consequently, since the bacteria is somewhat selective, the water quality is not severely affected. Then, most of the water can still be used after regenerating it—by cultivating more bacteria—to close the extraction loop.

Conventional mining and its related industries are highly criticized for being one of the largest sources of environmental pollution [8]. Therefore, the emission indicators were designed to estimate and compare the chief contaminants between both methods. Regarding TAE—$CO_2$ emissions—, in-situ bioleaching's emissions are equivalent to 29% of those of conventional mining. The reason for this decline in emissions is associated with the fact that in-situ bioleaching does not only use a fewer number of vehicles but also it does not use explosives in the production phase. As for the wastewater generation, the traditional method produces 82 times more wastewater than in-situ bioleaching. The main reason is that the latter approach optimizes water use by losing only around 20% in post-processing and within the rock during the extraction stage. Finally, the waste rock extracted is linked to the development works except for the drilling drifts and feeding and drainage boreholes—because they consist of ore—. Concerning this matter, the waste rock generated by means of in-situ bioleaching is 95% lesser than for the conventional method. So, emission-wise speaking, in-situ bioleaching demonstrates that it can provide significant benefits that traditional ways cannot. This improvement in emission generation responds to the increasing environmental concern and regulations that must be abided by the mining industry.

In terms of efficiency, as it was mentioned, conventional mining has a higher extraction efficiency than in-situ bioleaching. Despite that, the water consumption efficiency, namely the water recycling ratio, was reduced by 29% for the conventional method. Ergo, demonstrating that in-situ bioleaching makes better use of water in general. The extraction intensity represents the amount of ore that is extracted (TMP) with respect to the development works carried out. As a result, even if the amount of material processed is larger, the development needed is much more significant as well for the traditional method, so the EI is 17% of what it is for in-situ bioleaching. Accordingly, for the conventional way, there is considerably more development needed to extract the ore. Lastly, and of paramount importance is the environmental inefficiency. Although the quantity of material processed is not so different for both approaches, it is clear that the corresponding environmental consequences—TAE, TWWG, and TWRG—vary enormously from one method to the other, especially in wastewater generation. That being said, moving from conventional towards innovative ways like in-situ bioleaching could trigger a reduction of 96% in the E-in.

Altogether, both methods display benefits and disadvantages in the different aspects studied. While in terms of productivity, conventional mining still leads, in terms of overall consumption, emissions generated, and efficiency, in-situ bioleaching demonstrates to be a promising approach that must be considered. It is essential to realize that this analysis was made on one specific deposit with a defined grade of indium. Still, the calculated relations—mainly production-wise—can change when the grade varies. Because of this, an analysis can be made based on other indium-containing deposits, such as the Saxore Project, which is located in the same region as the studied deposit and has higher indium concentrations of 150 to 500 ppm [82].

For this reason, a first approximation to what could be the technical break-even point for the use of in-situ bioleaching was determined (Figure 7.10). Since the in-situ bioleaching recovery rate depends on the bacteria's selectivity and the lixiviant flow throughout the ore, the production is the same regardless of the change in grade. By way of contrast, the conventional method shows a consistent growth in annual production when the grade increases, as the production is based on the physical extraction of the ore per year. In this way, these behaviors are entirely consistent with the literature, given that conventional methods are usually highly efficient with higher grades, and leaching methods were developed for medium-to-low grades. Under such circumstances, the break-even point at which the annual production is the same for both technologies is a grade of 9.2 ppm. Whereby, below that limit, in-situ bioleaching would be a more favorable technology in terms of yearly production.

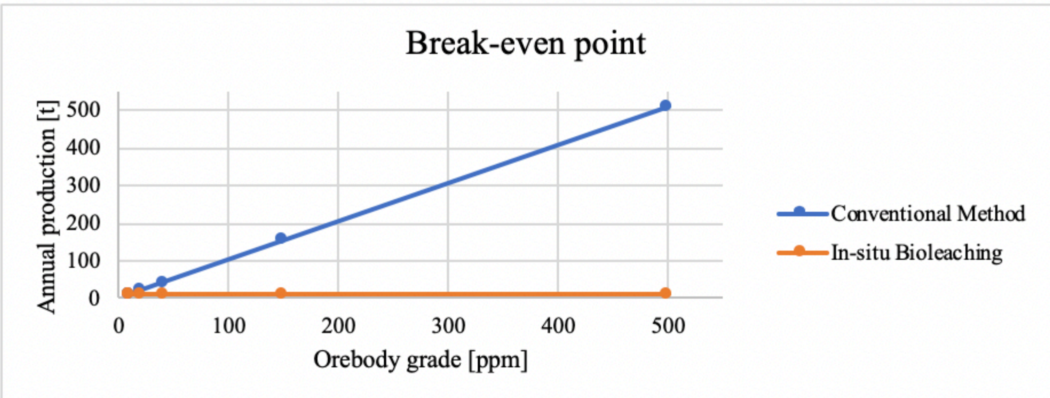


Figure 7.10 Conventional Method vs. In-situ Bioleaching Break-even point

# 8 Conclusions and Further Work

## 8.1 Conclusions

The work developed during this thesis portrays a valid contribution to the mining industry's purpose to meet "sustainable mining" and sustainable development goals. Since the main reasons why the need for strategic elements is continuously increasing and why the high-grade ore deposits are being depleted were successfully explained. Likewise, it has stated that a change in mining technology is fundamental to avoid a shortage of strategic elements in the future, and to ensure a proper supply while becoming more "environmentally friendly". As a consequence, it was reported that new technologies, like in-situ bioleaching, now ought to be developed to cope with the ever-stricter environmental regulations and more complex realities of ore bodies.

In-situ bioleaching can apply the circular economy principles in various steps of the process, particularly when implemented in an optimal scenario. In the broader picture, it deals with the "re-use" principle by being ideal to mine in a more sustainable manner previously exploited and un-profitable ore bodies, which are currently considered as "waste rock", as explained in Chapter 2.1. In this way, the development of this method supports the inclusion of the primary supply of raw materials in the circular economy concept, which refers to the mining industry. Similarly, at the mine site level, CE principles can be applied with this approach as well. The "reduce" principle is substantially represented in all of the main activities undertaken, such as the overall consumption of energy and natural resources, and the total emissions produced by this mining activity. Besides, the "recycle" principle is mainly present in the water management of the process, as it was mentioned earlier, 80% of the water can be recycled within the hydraulic loop, preserving the natural resource. All in all, this work enlightens how the mining industry is making an effort to meet the circular economy objectives.

The framework for modelling mineral exploitation flows of mining methods established by this work aimed to evaluate different methods when applied to an equivalent deposit. Thus, MFA-based key performance indicators were developed in terms of production, consumption, emissions generated, and efficiency. Then, to evaluate the indicators, the theoretical design of the in-situ bioleaching mine had to be done. With this intention, the in-situ bioleaching mine concept developed in this work comprised the target element production, mine dimensioning, development works, personnel, and machinery required. Additionally, it included the hydraulic system design, necessary consumptions, and emissions generated. The design made was based on a real-life size deposit with the properties of "Reiche Zeche" mine and another theoretical model previously developed by Louis Schaarschmidt that performed the conventional method described in Chapter 7.1. Lastly, the evaluation of the indicators for both of the concepts was conducted. The assessment for a potential upscaling opportunity for in-situ bioleaching resulted in significant improvements when it comes to energy and resource consumption, emissions, and overall efficiency. Although, these benefits are at the expense of the total production and subsequently profits. Anyhow, notwithstanding the technical facts disclosed in this analysis, a final decision on which method is more favorable must also consider the economic aspect for every stage of the process, which is vital when evaluating the implementation of a mining method.

## 8.2 Further Work

This thesis provides a general overview and a first approximation of how in-situ bioleaching could be implemented on an industrial scale, and its consequences in terms of production, consumption, emissions, and efficiency. The latter is possible with the information available from the test-site at "Reiche Zeche" mine. However, since the process is as of yet in its early stages of development, several other investigations and tests must be carried out to improve the technology readiness level of the method. In terms of bacterial use, other microorganisms can be evaluated. Similarly, the conditions for bacterial work could be altered to enhance the selectivity and hence the recovery rate of the target elements. The most-relevant bacterial-related parameters that can be optimized are temperature, humidity, pH, oxygen level, and other possible nutrients or supplements for the microorganisms.

Moreover, concerning the test-site layout, there are several upgrading opportunities. For instance, parameters such as the borehole diameter, distance between boreholes, the permeability enhancement technology, working flow, and pressure can be varied to find the optimal productivity combination. In conclusion, regardless of the effort that will come ahead of this work, the indicators developed here will continue to be valid for future assessment of mining methods. Equally, the established framework can even be complemented with additional tailored-made indicators applicable to the specific case for a more detailed analysis.

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# Appendix

# Appendix A: Conventional method – Development works

| | | |
|---|---|---|
| Decline | Shape | zic-zac |
| | Gradient [%] | 15 |
| | Amount | 1 |
| | Length [m] | 2447,01 |
| | Cross section [m2] | 36,42 |
| | Method | drill and blast |
| | Waste tonnage [t] | 249569,37 |
| Footwall drifts | Amount | 12 |
| | Length [m] | 500 |
| | Cross section [m2] | 36,40 |
| | Waste tonnage [t] | 611520 |
| Drilling drifts (ore drifts) | Amount | 12 |
| | Length [m] | 500 |
| | Cross section [m2] | 33 |
| | Ore tonnage [t] | 554400 |
| Drawpoints | Amount | 420 |
| | Length [m] | 20 |
| | Cross section [m2] | 20,25 |
| | Spacing [m] | 10 |
| | # per stope | 5 |
| | Waste tonnage [t] | 476280 |
| Crosscuts | Amount | 84 |
| | Length [m] | 20 |
| | Cross section [m2] | 20,25 |
| | Waste tonnage [t] | 95256 |
| Ventilation boreholes | Amount | 2 |
| | Airflow [m3/s] | 95,81 |
| | Diameter [m] | 1,5 |
| | Length [m] | 370 |
| | Waste tonnage [t] | 1307,69 |

## Appendix B: Conventional method – Electrical power and water supply

### Electrical power

| | |
|---|---|
| Conventional (crushing & sorting, milling, regrind, magnetic separation, flotation and utilities) [kWh/year] | 47.250.354 |
| Mine ventilation requirement [kWh/year] | 2.759.400 |
| Specific drilling energy for the rock type [kwh/year] | 126.335.264,80 |

### Water

| | |
|---|---|
| Total requirement [$m^3$/year] | 1.161.771,76 |
| Processing plant [$m^3$/year] | 1.000.000 |
| Total backfill operation [$m^3$/year] | 158.411,76 |
| Dust control (mainly through water and PPE) [$m^3$/year] | 3.360 |

## Appendix C: Conventional method – Air emissions

**Vehicles**

| Vehicle | Amount | Engine Power [kW] | Diesel engine efficiency | Qt [MJ/s] | Diesel LHV [MJ/L] | volumetric flow [L/s] | CO2 emissions in diesel [kg/L] | Estimated operation time per day [min/day] | CO2 emissions [t/year] |
|---|---|---|---|---|---|---|---|---|---|
| Landcruiser | 2 | 140 | 0,35 | 0,40 | 36 | 0,011 | 2,660 | 720 | 858,01 |
| Hilux | 5 | 110 | | 0,31 | | 0,009 | | 360 | 842,69 |
| Production drill (Sandvik DU421) | 1 | 110 | | 0,31 | | 0,009 | | 360 | 168,54 |
| Jumbo drill (Sandvik DD422iE) | 1 | | | 0,00 | | 0,000 | | 360 | 0 |
| Cat R2900G | 1 | 305 | | 0,87 | | 0,024 | | 756 | 981,35 |
| Cat R1300G | 1 | 123 | | 0,35 | | 0,010 | | 756 | 395,76 |
| Rock bolting (Sandvik DS311) | 1 | 62 | | 0,18 | | 0,005 | | 360 | 94,99 |
| Blasting (MAN D0834) | 1 | 110 | | 0,31 | | 0,009 | | 360 | 168,54 |
| Hauling (Bell B45E) | 7 | 390 | | 1,11 | | 0,031 | | 450 | 5228,50 |
| | | | | | | | | TOTAL | 8738,37 |

**Explosives**

| | |
|---|---|
| CO2 per anfo [tco2/tanfo] | 0,19 |
| Explosive/day [kg/day] | 2566,96 |
| Round thickness [m] | 2,72 |
| Daily production [t/day] | 5133,93 |
| Explosives/year [tanfo/year] | 862,50 |
| Co2 emissions [tco2/year] | 163,01 |

## Appendix D: Conventional method – Water Recycling Rate

| Processing plant water | Input [t/h] | Return [t/h] |
|---|---|---|
| Milling area | 280 | |
| Process water distribution | 545 | |
| Concentrate thickener | | 149 |
| Concentrate filtration | | 5 |
| Tails thickener | | 367 |
| Final concentrate thickener | | 24 |
| TOTAL | 825 | 545 |
| Water recycling rate | 66% | |

## Appendix E: In-situ bioleaching - Development works

| | | |
|---|---|---|
| Decline | Shape | zic-zac |
| | Gradient [%] | 15 |
| | Amount | 1 |
| | Length [m] | 2.536,18 |
| | Cross section [$m^2$] | 36,42 |
| | Method | drill and blast |
| | Waste tonnage [t] | 258.663,60 |
| Footwall drifts | Amount | 6 |
| | Length [m] | 500 |
| | Cross section [$m^2$] | 36,42 |
| | Waste tonnage [t] | 305.968,13 |
| Drilling drifts (ore drifts) | Amount | 6 |
| | Length [m] | 500 |
| | Cross section [$m^2$] | 129,81 |
| | Ore tonnage [t] | 1.090.401,49 |
| Crosscuts | Amount | 6 |
| | Length [m] | 20 |
| | Cross section [$m^2$] | 20,25 |
| | Waste tonnage [t] | 6.804 |

| | | |
|---|---|---|
| Pipeline boreholes | Amount | 8 |
| | Diameter [m] | 1,50 |
| | Length [m] | 370 |
| | Waste tonnage [t] | 14.646,10 |
| Ventilation boreholes | Amount | 2 |
| | Airflow [$m^3/s$] | 32,55 |
| | Diameter [m] | 1,50 |
| | Length [m] | 370 |
| | Waste tonnage [t] | 1.307,69 |
| Production "Feeding" boreholes" | Amount | 66.192 |
| | Volume [$m^3$] | 16.793,64 |
| | Ore tonnage [t] | 47.022,21 |
| Production "drainage" boreholes | Amount | 71.280 |
| | Volume [$m^3$] | 18.870,81 |
| | Ore tonnage [t] | 52.838,27 |

## Appendix F: In-situ bioleaching – Annual production

| Total production | | | |
|---|---|---|---|
| Element | [ppb] | [kg/L/year] | Production [t/year] |
| In | 33,24 | 6,57E-07 | 9,41 |
| Na | 19.890,77 | 3,93E-04 | 5.630,83 |
| Al | 2.174.846,15 | 4,30E-02 | 615.672,20 |
| K | 36.927,69 | 7,30E-04 | 10.453,78 |
| Cr | 81,69 | 1,61E-06 | 23,12 |
| Mn | 259.269,23 | 5,12E-03 | 73.395,93 |
| Fe | 1.239.000,00 | 2,45E-02 | 350.745,66 |
| Cu | 33.406,15 | 6,60E-04 | 9.456,87 |
| Zn | 496.192,31 | 9,81E-03 | 140.465,94 |
| Ge | 9,94 | 1,96E-07 | 2,81 |
| Sr | 415,85 | 8,22E-06 | 117,72 |
| Y | 809,31 | 1,60E-05 | 229,11 |
| Zr | 46,29 | 9,15E-07 | 13,10 |
| Nb | 2,52 | 4,99E-08 | 0,71 |
| Rh | 0,68 | 1,34E-08 | 0,19 |
| Cd | 4.842,39 | 9,57E-05 | 1.370,82 |
| Sn | 152,01 | 3,00E-06 | 43,03 |
| La | 273,27 | 5,40E-06 | 77,36 |
| Ce | 698,92 | 1,38E-05 | 197,86 |
| Pr | 105,86 | 2,09E-06 | 29,97 |
| Nd | 505,08 | 9,98E-06 | 142,98 |
| Sm | 130,36 | 2,58E-06 | 36,90 |
| Eu | 23,98 | 4,74E-07 | 6,79 |
| Gd | 150,77 | 2,98E-06 | 42,68 |
| Tb | 23,81 | 4,71E-07 | 6,74 |
| Dy | 143,66 | 2,84E-06 | 40,67 |
| Ho | 26,72 | 5,28E-07 | 7,56 |
| Er | 76,46 | 1,51E-06 | 21,65 |
| Tm | 9,73 | 1,92E-07 | 2,75 |
| Yb | 64,24 | 1,27E-06 | 18,18 |
| Lu | 8,65 | 1,71E-07 | 2,45 |
| Hf | 47,13 | 9,32E-07 | 13,34 |
| Re | 0,62 | 1,22E-08 | 0,17 |
| Pb | 1.380,62 | 2,73E-05 | 390,84 |
| U | 22,27 | 4,40E-07 | 6,30 |
| | | Total | 1.208.676,46 |

# Appendix G: In-situ bioleaching – Hydraulic system

## Water requirement and head loss in piping system

| Boreholes in one stope | | |
|---|---|---|
| Dimension | Feeding borehole | Drainage borehole |
| Diameter [m] | 0,053 | 0,053 |
| Length [m] | 115 | 120 |
| Spacing [m] | 0,6 | 0,6 |
| Volume [m3] | 0,25 | 0,26 |
| Amount | 2.758 | 2.970 |
| Total volume [L] | 699.735,20 | 786.283,78 |

| Borehole grid per stope | |
|---|---|
| Feeding boreholes per line (125 m) | 197 |
| Drainage boreholes per line (125 m) | 198 |
| Number of feeding lines | 14 |
| Number of drainage lines | 15 |

| Bioleaching solution | |
|---|---|
| Volume [L/stope] | 1.271.621,80 |
| Flow /stope [L/h] | 74.006,33 |
| Flow/ borehole [L/h] | 26,83 |
| Total lixiviant flow/stope [L/year] | 596.787.072,00 |

| Storage tanks | |
|---|---|
| Volume [m3] | 74,01 |
| Length [m] | 3 |
| Diameter [m] | 5,60 |
| Number of storage tanks/ stope | 2 |

| Lixiviant requirement | |
|---|---|
| Volume / stope [m3] | 1.271,62 |
| Total volume [m3] | 30.518,92 |

| Head loss | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feeding | | | | | | | | | | | | |
| Node | Q [m3/s] | A_1 [m2] | d_1 [mm] | d_1 [in] | D [m] | A [m] | V [m/s] | Re | f | L [m] | h_L [m] | h_L_Tees [m] |
| 1 | 2,06E-02 | 1,03E-02 | 114,40 | 4 | 0,1 | 8,11E-03 | 2,54 | 2,58E+05 | 1,79E-02 | 1 | 5,79E-02 | 6,55E-02 |
| 2 | 1,91E-02 | 9,54E-03 | 110,24 | 4 | 0,1 | 8,11E-03 | 2,35 | 2,39E+05 | 1,81E-02 | 1 | 5,02E-02 | 5,65E-02 |
| 3 | 1,76E-02 | 8,81E-03 | 105,91 | 4 | 0,1 | 8,11E-03 | 2,17 | 2,21E+05 | 1,82E-02 | 1 | 4,31E-02 | 4,82E-02 |
| 4 | 1,62E-02 | 8,08E-03 | 101,40 | 4 | 0,1 | 8,11E-03 | 1,99 | 2,02E+05 | 1,84E-02 | 1 | 3,66E-02 | 4,05E-02 |
| 5 | 1,47E-02 | 7,34E-03 | 96,69 | 4 | 0,1 | 8,11E-03 | 1,81 | 1,84E+05 | 1,86E-02 | 1 | 3,06E-02 | 3,34E-02 |
| 6 | 1,32E-02 | 6,61E-03 | 91,72 | 4 | 0,1 | 8,11E-03 | 1,63 | 1,66E+05 | 1,88E-02 | 1 | 2,51E-02 | 2,71E-02 |
| 7 | 1,17E-02 | 5,87E-03 | 86,48 | 4 | 0,1 | 8,11E-03 | 1,45 | 1,47E+05 | 1,91E-02 | 1 | 2,01E-02 | 2,14E-02 |
| 8 | 1,03E-02 | 5,14E-03 | 80,89 | 4 | 0,1 | 8,11E-03 | 1,27 | 1,29E+05 | 1,94E-02 | 1 | 1,57E-02 | 1,64E-02 |
| 9 | 8,81E-03 | 4,41E-03 | 74,89 | 4 | 0,1 | 8,11E-03 | 1,09 | 1,10E+05 | 1,98E-02 | 1 | 1,18E-02 | 1,20E-02 |
| 10 | 7,34E-03 | 3,67E-03 | 68,37 | 4 | 0,1 | 8,11E-03 | 0,91 | 9,20E+04 | 2,04E-02 | 1 | 8,39E-03 | 8,36E-03 |
| 11 | 5,87E-03 | 2,94E-03 | 61,15 | 4 | 0,1 | 8,11E-03 | 0,72 | 7,36E+04 | 2,12E-02 | 1 | 5,57E-03 | 5,35E-03 |
| 12 | 4,41E-03 | 2,20E-03 | 52,96 | 4 | 0,1 | 8,11E-03 | 0,54 | 5,52E+04 | 2,23E-02 | 1 | 3,30E-03 | 3,01E-03 |
| 13 | 2,94E-03 | 1,47E-03 | 43,24 | 4 | 0,1 | 8,11E-03 | 0,36 | 3,68E+04 | 2,41E-02 | 1 | 1,58E-03 | 1,34E-03 |
| 14 | 1,47E-03 | 7,34E-04 | 30,57 | 4 | 0,1 | 8,11E-03 | 0,18 | 1,84E+04 | 2,79E-02 | 1 | 4,59E-04 | 3,34E-04 |
| | | | | | | | | | | TOTAL_h_L | 0,63 | m |

| Head loss | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pump | Q [m3/s] | A_1 [m2] | d_1 [mm] | d_1 [in] | D [m] | A [m] | V [m/s] | Re | f | L [m] | h_L [m] |
| Drainage | 2,06E-02 | 1,03E-02 | 114,40 | 4 | 0,1 | 8,11E-03 | 2,54 | 2,58E+05 | 1,79E-02 | 182 | 10,50 |
| 1 Level-ouput | 2,06E-02 | 1,03E-02 | 114,40 | 4 | 0,1 | 8,11E-03 | 2,54 | 2,58E+05 | 1,79E-02 | 510 | 29,50 |
| 2 Level-ouput | 2,06E-02 | 1,03E-02 | 114,40 | 4 | 0,1 | 8,11E-03 | 2,54 | 2,58E+05 | 1,79E-02 | 647 | 37,44 |
| 3 Level-ouput | 2,06E-02 | 1,03E-02 | 114,40 | 4 | 0,1 | 8,11E-03 | 2,54 | 2,58E+05 | 1,79E-02 | 774 | 44,80 |

## Pumps requirements and selection

| Feeding Pump | |
|---|---|
| Head loss per line [m] | 3,42 |
| Total head loss [m] | 4,05 |
| Total head requirement [m] | 24,43 |
| Total pressure demand [bar] | 2,40 |
| Pipe length [m] | 1668 |
| Pump power [kW] | 4,93 |
| Pump flow [m3/h] | 74 |

| Drainage Pump | |
|---|---|
| Total head loss [m] | 10,50 |
| Total head requirement [m] | 30,89 |
| Total pressure demand [bar] | 3,0 |
| Pipe length [m] | 182 |
| Pump power [kW] | 6,23 |
| Pump flow [m3/h] | 74 |

| Output pumps | 1 level | 2 level | 3 level |
|---|---|---|---|
| Total head loss [m] | 29,50 | 37,44 | 44,80 |
| Total head requirement [m] | 49,89 | 57,83 | 65,18 |
| Total pressure demand [bar] | 4,9 | 5,7 | 6,4 |
| Pipe length [m] | 510 | 647,18 | 774,36 |
| Pump power [kW] | 10,06 | 11,66 | 13,15 |
| Pump flow [m3/h] | 74 | 74 | 74 |

| Pumps | | | | | |
|---|---|---|---|---|---|
| Pump type | Feeding | Drainage | 1 Level-ouput | 2 Level-ouput | 3 Level-ouput |
| Amount | 24 | 24 | 8 | 8 | 8 |
| Model | CRN 64-2-1 | CRN 64-3-2 | CRN 64-3 | CRN 64-4-1 | CRN 64-5-2 |
| Power [kW] | 11 | 15 | 18,5 | 22 | 30 |
| Efficiency | 79% | 79% | 79% | 79% | 79% |
| Effective power [kW] | 8,69 | 11,85 | 14,615 | 17,38 | 23,7 |

## Appendix H: In-situ bioleaching – Personnel and machinery

| Personnel | | | |
|---|---|---|---|
| Function | Shift 1 (6 - 14 hr) [workers] | Shift 2 (14 - 22 hr) [workers] | Shift 3 (22 - 6 hr) [workers] |
| Monitoring team | 2 | 2 | 2 |
| Helper | 1 | 1 | 1 |
| Foreman | 1 | 1 | 1 |
| Electrician | 1 | 1 | 1 |
| Locksmith | 1 | 1 | 1 |
| Safety personnel | 1 | 1 | 1 |
| Engineer | 1 | 0 | 0 |
| Total | 8 | 7 | 7 |
| Total workers | 22 | | |

| Machinery | | | |
|---|---|---|---|
| Equipment | Function | Amount | Engine Power [kW] |
| Toyota Landcruiser | Production | 2 | 140 |
| Toyota Hilux | Production | 2 | 110 |
| Long hole drill(Diamec 232) | Development | 1 | 15 |
| Jumbo drill(Sandvik DD422iE) | Development | 1 | 195 |
| Cat R1300G (development mucking) | Development | 1 | 123 |
| Rock bolting(Sandvik DS311) | Development | 1 | 62 |
| Blasting (MAN D0834) | Development | 1 | 110 |
| Hauling (Bell B45E) | Development | 1 | 390 |
| Fan AL14-1100 (full-time op.) | Production | 1 | 110 |

## Appendix I: In-situ bioleaching – Electrical power supply

| | |
|---|---|
| Mine ventilation requirement [kWh/year] | 963.600 |
| Specific drilling energy for the rock type [kWh/year] | 17.904.506 |
| Lixiviant and pregnant solution pumps [kWh/year] | 9.580.032 |

# Appendix J: In-situ bioleaching – Air requirement

| Vehicle | Function | Amount | Engine Power [kW] | Operation time [h/day] | Air required [m3/day] |
|---|---|---|---|---|---|
| Toyota Landcruiser | Production | 2 | 140 | 12 | 806.400 |
| Toyota Hilux | Production | 2 | 110 | 6 | 316.800 |
| Long hole drill(Diamec 232) | Development | 1 | 15 | 6 | 21.600 |
| Jumbo drill(Sandvik DD422iE) | Development | 1 | 195 | 6 | 280.800 |
| Cat R1300G (development mucking) | Development | 1 | 123 | 12,6 | 371.952 |
| Rock bolting(Sandvik DS311) | Development | 1 | 62 | 6 | 89.280 |
| Blasting (MAN D0834) | Development | 1 | 110 | 6 | 158.400 |
| Hauling (Bell B45E) | Development | 1 | 390 | 7,5 | 702.000 |
| | | | | Total air required [m3/day] | 2.747.232 |

| Air requirement | |
|---|---|
| Air per Person [m3/min/person] | 2 |
| Air per vehicle [m3/min*kw] | 4 |
| Total air required [m3/day] | 2.812.032 |
| Total air required [m3/s] | 32,5 |

| | |
|---|---|
| Workers/shift [workers] | 25 |
| Time underground [h/day] | 21,6 |
| Total air required [m3/day] | 64.800 |

| Pressure loss | | | | | | |
|---|---|---|---|---|---|---|
| Characteristics | Decline | Production drift | Footwall drift | Crosscut | Ventilation borehole | Pipeline borehole |
| Length [m] | 1223,5 | 1000 | 1000 | 20 | 370 | 370 |
| Cross section area [m2] | 36,4 | 130 | 36,4 | 20 | 1,77 | 1,77 |
| Air velocity [m/s] | 0,9 | 0,3 | 0,9 | 1,6 | 18,4 | 18,4 |
| Hydraulic diameter [m] | 6,0 | 8,9 | 5,7 | 4,5 | 1,5 | 1,5 |
| Pressure loss [Pa] | 0,8 | 0,1 | 0,712 | 0,1 | 232,6 | 232,61 |
| Total pressure loss [Pa] | 0,8 | 0,32 | 2,13 | 0,35 | 465,21 | 1860,86 |
| Total pressure loss [Pa] | 2329,7 | | | | | |

| Friction coefficients | | |
|---|---|---|
| Ventilation borehole | 0,005 | No support |
| Decline/Footwall drifts/Crosscuts | 0,0092 | Shotcrete |
| Production drift | 0,027 | No support, bumpy since it is blasted |

| Mine ventilation | |
|---|---|
| Min. Velociiy [m/s] | 0,3 |
| Max. Velocity [m/s] | 6 |
| Elevation [m] | 1000 |
| Air pressure [m] | 891,2 |
| Gas constant [J/kg*K] | 287,058 |
| Air density [kg/m3] | 1,112 |

| Fan AL14-1100 | |
|---|---|
| Power [kW] | 110 |
| Air flow [m3/s] | 32 - 53 |
| Air pressure [Pa] | 2400 |

## Appendix K: In-situ bioleaching – Air emissions

### Vehicles

| Air (CO2) emissions | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle | Engine type | Amount | Engine Power [kW] | Diesel engine efficiency | Qt [MJ/s] | Diesel LHV [MJ/L] | volumetric flow [L/s] | CO2 emissions in diesel [kg/L] | Estimated operation time per day [min/day] | CO2 emissions (t/year) |
| Toyota Landcruiser | Diesel | 2 | 140 | 0,35 | 0,40 | 36 | 0,011 | 2,660 | 720 | 858,01 |
| Toyota Hilux | Diesel | 2 | 110 | | 0,31 | | 0,009 | | 360 | 337,08 |
| Long hole drill(Diamec 232) | Electric | 1 | 0 | | 0,00 | | 0,000 | | 360 | 0 |
| Jumbo drill(Sandvik DD422iE) | Electric | 1 | 0 | | 0,00 | | 0,000 | | 360 | 0 |
| Cat R1300G (development mucking) | Diesel | 1 | 123 | | 0,35 | | 0,010 | | 756 | 395,76 |
| Rock bolting(Sandvik DS311) | Diesel | 1 | 62 | | 0,18 | | 0,005 | | 360 | 94,99 |
| Blasting (MAN D0834) | Diesel | 1 | 110 | | 0,31 | | 0,009 | | 360 | 168,54 |
| Hauling (Bell B45E) | Diesel | 1 | 390 | | 1,11 | | 0,031 | | 450 | 746,93 |
| | | | | | | | | | TOTAL | 2601,30 |