

2021

Mining energy consumption as a function of ore grade decline: the case of lead and zinc

Follow this and additional works at: <https://jasm.gig.eu/journal-of-sustainable-mining>



Part of the [Oil, Gas, and Energy Commons](#)

Recommended Citation

Magdalena, Ricardo; Valero, Alicia; Palacios, Jose-Luis; and Valero, Antonio (2021) "Mining energy consumption as a function of ore grade decline: the case of lead and zinc," *Journal of Sustainable Mining*: Vol. 20 : Iss. 2 , Article 5.

Available at: <https://doi.org/10.46873/2300-3960.1060>

This Research Article is brought to you for free and open access by Journal of Sustainable Mining. It has been accepted for inclusion in Journal of Sustainable Mining by an authorized editor of Journal of Sustainable Mining.

Mining energy consumption as a function of ore grade decline: The case of lead and zinc

Ricardo Magdalena ^{a,*}, Alicia Valero ^a, Jose-Luis Palacios ^b, Antonio Valero ^a

^a CIRCE Institute – Universidad de Zaragoza, Spain

^b Departamento de Ingeniería Mecánica, Escuela Politécnica Nacional de Ecuador, Ecuador

Abstract

Demand for raw materials is increasing exponentially. To satisfy that demand, more minerals need to be mined from the Earth's crust. As a result, minerals are being exhausted, and ore grades decline. Lower ore grade mines also mean more energy, which in turn entails fossil fuel emissions and more climate change. This paper estimates the specific energy for the beneficiation process of metals lead and zinc as case studies. The evaluation is performed with specialized software, HSC Chemistry which assesses the specific energy for every stage: comminution, flotation, and refining. Different scenarios have been established to simulate the behavior of a mine when it approaches depletion. Preliminary results show that energy consumption for lead would increase by five times when compared to the current situation if ore grades decrease until the level of tailings, while for zinc by almost two.

Keywords: energy, ore grade, lead, zinc, beneficiation, tailings

1. Introduction

Modernization and consumer culture are increasing the demand for materials to satisfy the needs of society [1]. In this respect, electric and electronic equipment (EEE) or renewable energies are developing very fast, relying on the use of a considerable amount of raw materials [2]. For instance, the EEE trend is that this industry will increase in the coming years at 3–5% [3]. More metals need to be extracted every year to satisfy this exponential demand, for which more energy needs to be brought into play [4], [5]. Mining energy still relies almost completely on fossil fuels, exacerbating the liberation of greenhouse gases to the atmosphere and accelerating climate change. It is a fact that mining is among the most polluting industries [6].

Viederman [7] defined that a sustainable society aims to ensure the health of human life, culture, and natural capital for the present and future generations. Preserving the mineral capital can only be achieved through recycling and circular economy,

since minerals are limited in the Earth's crust. Accordingly, the energy required to extract the same amount of materials spirals up [8], since as we will see in this paper, extraction follows a negative logarithmic pattern with the ore grade. This is a consequence of the Second Law of Thermodynamics. Can we then expect more fossil fuel use and GHG emissions due to mining in the future? What would be the increase in energy consumption if we extracted metals from tailings? Is there an ore grade limit considering current technology?

Each year, minerals are being extracted, and the ore grade of mines is decreasing [9]. As a result, the energy to beneficiate the mineral is growing due to decreased concentration in the crust [8]. Therefore, it becomes essential to estimate future extraction costs and so anticipate potential raw material shortages. This paper will analyze the influence of ore grade decline on energy consumption for two significant metals, lead, and zinc. To that end, a specialized software called HSC Chemistry will be applied, analyzing all the processes required to mine, beneficiate the mineral, and finally refine them. The simulation allows us to obtain the energy consumption as a function of the starting ore grade,

Received 4 March 2021; revised 20 April 2021; accepted 22 April 2021.
Available online 15 June 2021

* Corresponding author.
E-mail address: rmagdalena@unizar.es (R. Magdalena).

<https://doi.org/10.46873/2300-3960.1060>

2300-3960/© Central Mining Institute, Katowice, Poland. This is an open-access article under the CC-BY 4.0 license (<https://creativecommons.org/licenses/by/4.0/>).

providing us with valuable insights to the questions raised above.

2. Lead and zinc as commodities

Lead was discovered more than 5000 years ago. Its use has been essential for civilization development, historically used to create ornaments and statues to decorate castles and cathedrals [10]. Nowadays, due to its specific properties [11], lead is the fifth most used metal, found in many different applications such as in storage batteries, sheathing electric cables, construction, tanks, and ammunition [10]. Lead is particularly essential in energy storage, as the most common batteries are lead-acid [12], vastly used in the automotive industry. According to the International Lead & Zinc Study Group, the demand for the lead rose by 2.7% in 2018 due to the increased Chinese (3.4%) and United States (3.1%) demand [13]. For the coming years, demand is expected to increase at a rate of 4.2%, with Australia experiencing the most significant growth [13]. Fig. 1 shows the lead production trend for the last decade, where China stands out over the rest producing countries. That said, Australia may play a major role as it contains the highest reserves of lead in the world, with more than 24,000 Mt [14]. The second country which follows Australia in reserves is China, with more than 18,00 Mt but already producing more than 2,00 Mt per year [14].

Regarding zinc, even if it was already known in Roman times, it was not recognized as a single metallic element until the 16th century. It was first called zinckum and eventually zinc in 1743 [10]. Zinc metal is the fourth most used metal, with extensive applications such as in galvanization, alloys (especially brass), and even zinc sulfide for electroluminescence photoconductivity [10]. Since zinc is usually found with lead in nature, it is extracted as a by-product of the latter. The beneficiation process carried out to extract lead facilitates the separation of zinc as well.

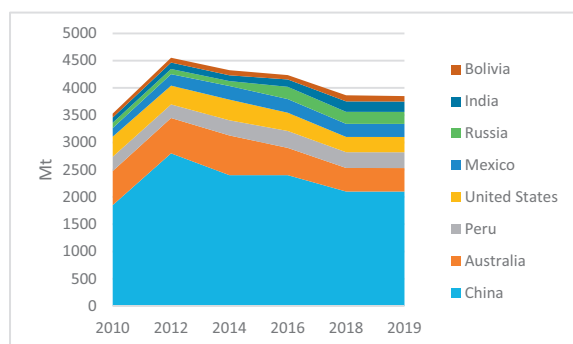


Fig. 1. World lead production [Mt] [14], [15].

Zinc mine production rose by 1.1% in 2017, and it was expected to increase this figure up to 5.1% in 2018 [13]. This increase is due to Dugald River Mine's opening in late 2017 in Australia and the Castellanos Mine opening in late 2017 in Cuba. Fig. 2 shows zinc production in the last decade, showing that after a small peak in 2012, production is increasing again. Therefore, it is expected to have a significant increase in the upcoming decades according to different authors [16], [17], which means that in that time, almost 100% of zinc should be obtained from secondary resources (being 15% nowadays [18]).

3. Case study

Based on previous studies [8, 18–20], the specific energy required for concentrating lead and its by-product, zinc, will be assessed. The reason to focus on these two metals jointly is that they are usually found together in nature [23] and hence their geological distribution is similar [24]. For the analysis, models in HSC software have been carried out for every metal to estimate the energy required for their processing. HSC Chemistry [25] is specialized software where thermodynamic and mineral processing calculations can be carried out.

Fig. 3 shows the general flowchart for the mining, beneficiation, and refining of lead and zinc. It has been developed following guidelines found in technical reports: Prairie Creek mine in Canada [26] with a capacity converter of 87 tons per hour [tph], Platosa Silver–Lead–Zinc in Mexico [27] with a capacity converter of 83 tph, and Ying property mine in China [28], with a capacity converter of 74 tph. Additionally, essential data to elaborate the flowsheet has been taken from specialized mineral processing books [29], [30], [31], while specific details for every process for the particular metals analyzed along with this paper have been consulted from different references [30, 31]. The aim of this paper is to try to understand how it would be the behavior of a mine when the ore grade decreases. Therefore, twelve different scenarios will be created

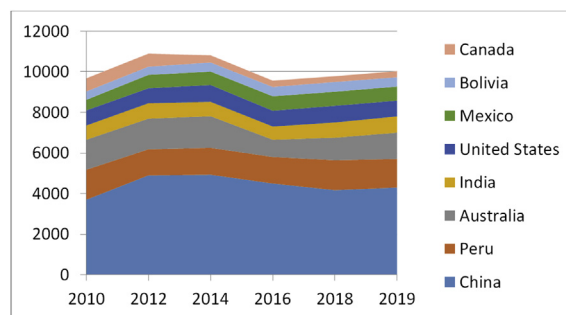


Fig. 2. Production of zinc by year [Mt] [19].

Concentration of PB-Zn

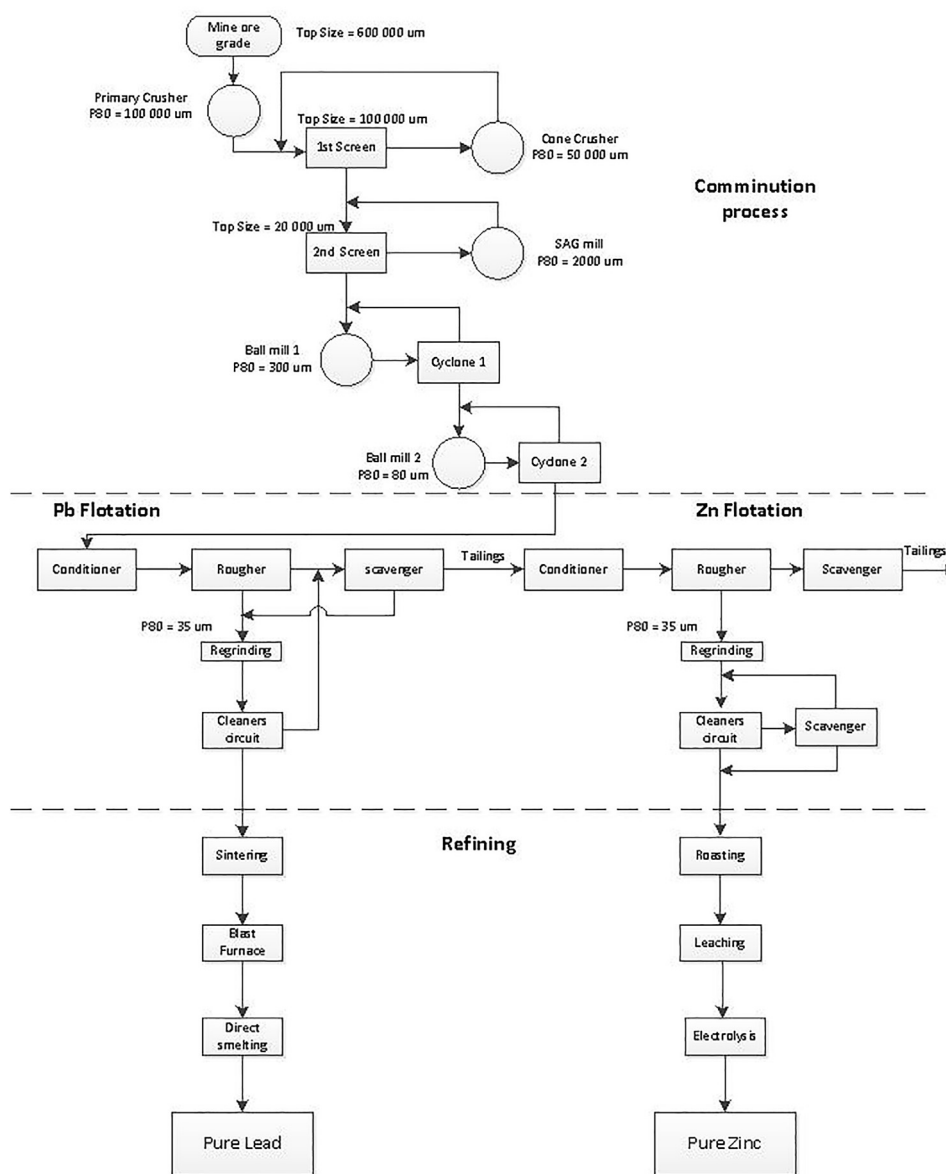


Fig. 3. Flowsheet of the beneficiation process for lead and zinc.

to calculate the energy needed to obtain a certain metal amount. The initial scenario will be carried out with the current ore grade, while the rest will be one-third of the previous, reaching very low values and simulating and predicting the problems that could appear in the future.

It should be stated from the outset that there are no similar mines, and therefore, the results obtained from every mine could be different. The results obtained for a generic mine can be used as a proxy for the rest, as the results show an estimation of the specific concentration energy when the ore grade decreases. In this paper, Ying property minerals have been chosen as a starting point for the simulation in

HSC [28]. There are many minerals as lead and zinc sources [34]. However, not all of them are abundant, or the amount of Pb and Zn in them is very low and are not cost-effective to use [30, 32–35]. This is why we use galena as the main source for lead, while sphalerite for zinc, both sulfide minerals relatively abundant and with high metal concentrations [38].

4. Methodology

4.1. HSC simulation

The feed chosen to introduce in the software is 800 tons per day [tpd], a rather high value since as the

concentration is reduced, more amount of rock needs to be processed. This initial feed has a maximum particle size of 600 mm. Three main energy inputs have been considered in the analysis, which will then be validated with bibliographic data: ore handling, concentration, and refining.

Ore handling entails the diesel used for transportation, machinery, and electricity production. After ore handling, the first stage is comminution, carried out through crushing and grinding machines to reduce the particle size until the rock is small enough to proceed with the next stage [39]. As calculated in [8], [21], [22], the comminution was computed with well-known formulas such as Bonds equation [27, 34], which is applied to calculate the specific energy required for the different mills used along the comminution process.

$$W = 10 W_i \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) EF_x \quad (1)$$

In Eq. (1), W_i is the work index, which is defined as the comminution parameter that expresses the resistance of the material to crushing and grinding, P_{80} is the diameter in microns through which 80% of the product passes, F_{80} is defined as the size through which 80% of the feed passes [31] and EF_x which is an efficiency factor, is an adjustment of the power calculated by utilizing efficiency factors dependent on the size of the mill, size, and type of media, type of grinding circuit, etc. [27, 36, 37].

The first stage (comminution process) aims to reduce the particle size down to 35 μm [27], using the flowsheet shown in Fig. 1. Comminution is divided into three main steps: Crushing, grinding, and regrinding. Crushing is carried out by a primary crusher, reducing the size to 100,000 μm , and then, the feed is sent to a screen, acting as a filter for particles higher than 100,000 μm . Any larger particle is diverted through a cone crusher, decreasing the size to 50,000 μm and passing through the same screen.

Once all the feed has passed through screen 1, another screen is introduced with a size filter of 20,000 μm , starting the grinding process. Particles,

which do not pass screen 2, are sent to the SAG mill to reduce the size to 2,000 μm , crossing the filter applied. A ball mill is the next step when all the feed is out of screen 2. The mill is used to minimize it down to 300 μm , adding a cyclone just right after to assure that all particles satisfy the size requirements. Similarly, Ball mill 2 reduces the size to 80 μm and allows the feed to go to flotation. It is important to mention that the comminution process has been developed according to the reduction ratio [27, 34, 38]. Table 1 has been elaborated to summarize all the numbers and to recap every process with its details.

Sulfide metals are the main sources to produce lead and zinc also because they are separated from the rest of the minerals applying flotation [44]. At this point, the separation between lead and zinc is produced, because in the first unit of the flotation process there are two outputs: lead-rich feed and the tailings, which are recirculated to a different flotation process, to enrich zinc. [45]. The flotation process consists of a rougher circuit followed by several cleaners and a retreat circuit [46]. This stage aims to make the wanted metals float by adding additives. The rest of the minerals (unfloated) are vacated to the tailings [40, 41]. As two different metals are wanted, two different processes will be carried out, setting up the volume and the number of cells with common values obtained from manufacturers data [25, 42] and institutions specialized in flotation cells [48].

The process ends with the refining stage. When the feed contains the concentration desired, pyrometallurgy follows to obtain pure lead. In contrast, hydrometallurgy and an electrolytic process is used to obtain pure zinc [36]. Pyrometallurgy is composed of sintering and the use of a blast furnace [49].

5. Results

As was previously explained, the comminution process is common for both minerals. Hence, in this section, the modeling results regarding the specific energy required for every unit in the comminution

Table 1. Details of the comminution process.

	Primary crusher	Cone crusher	SAG mill	Ball mill 1	Ball mill 2	Re-grinding	
						Pb	Zn
Feed [tph]	800	512	578	1,569	1,406	474	250
P80 [μm] ^a	100,000	50,000	2,000	300	80	35	35
F80 [μm] ^b	245,631	219,277	38,163	3,164	138	50	48

^a 80% of the passing size of the product [21].

^b 80% of the passing size of the feed [21].

process will be shown. Subsequently, the section will be divided to explain the flotation and refining process for every mineral, highlighting the values obtained.

5.1. Comminution process

To start with the calculation of every unit, it must be noted that the Work Index (W_i) selected to introduce in Eq. (1) is the same for both minerals as their proximity is very close, and the difference between them in final results cannot be appreciated. Thus, the value chosen to introduce as a W_i is 11 kWh/t, which is obtained from [50]. Furthermore, different efficiencies must be added according to Rowland efficiency factors (EF_x) obtained from a literature review [43].

Table 2 is elaborated to determine the energy used for the comminution process. Eq. (1) has been used to calculate the specific energy for every unit, while the machines selected and settings come from references [27, 48], proposing units able to supply the power demanded. The results obtained are in line with the literature [27, 42, 48, 49], all of them in the same order of magnitude. It can be seen that there is a different regrinding for lead and zinc.

5.2. Flotation process

The flotation process is a concentration technique that uses the difference of the surface properties to separate minerals [38]. The flotation circuit is composed of three elements: roughers, cleaners, and scavengers. Roughers receive the pulp coming from the mills. Then, valuable sulfides float,

obtaining a concentrate with many impurities [38]. Cleaners are commissioned to eliminate the impurities to obtain the concentrated mineral [38]. Scavengers are usually added right after the roughers in order to make the remaining sulfides that did not float in the rougher machine to float [38].

To simulate the behavior of a mine when the ore grade decreases, different scenarios will be created, reducing the initial concentration in the mine. This process will aim to increase the concentration until typical values required for the metallurgical process. Every scenario will contain a lower ore grade. This also means that more flotation units will be needed to obtain the same concentration.

The first scenario was developed with a typical value found in mines of 2.83 wt% and 6.29 wt% [26] for lead and zinc, respectively. The metal content needs to be increased to 45 wt% for lead and 52 wt% for zinc [36]. This is achieved through a rougher to start the separation. Due to their froth properties, galena floats in the surface while sphalerite is vacated through the tailings, starting a new flotation process.

The concentration stream from the rougher, containing galena, is passed through different cleaners and scavengers until the required concentration is reached. A regrinding process in between is used to make sure there are no particles larger than 35 μm . It must be mentioned that other tailings from flotation units are sent to the zinc flotation process to recover all possible minerals. Once all the sphalerite feed starts the flotation process, it is sent through a new rougher unit. After a regrinding and flotation process, the required pre-refining concentration is achieved.

More scenarios are created to simulate how each metal concentration's specific energy increases when the ore grade decreases. Scenario 1 represents the current ore grade, scenario 4 represents the tailings ore grade, scenario 8 represents the theoretical limit established by Sverdrup et al. [17], and scenario 12 represents a minimum concentration, very close to crustal concentrations.

Table 3 shows the results, highlighting that the last scenario created (12) entails the highest value of specific concentration energy as expected. It must be said that the flotation process for each mineral has been designed according to parameters obtained

Table 2. Power demand and energy required for the comminution process.

Equipment	Power demand [MW]	Specific energy [kWh/t-rock]
Primary crusher	0.60	0.75
Cone crusher	0.45	0.88
SAG mill	4.20	7.27
Ball mill 1	17.80	11.40
Ball mill 2	17.80	12.72
Re-grinding Pb	5.96	12.57
Re-grinding Zn	2.7	10.80

Table 3. Variation of the specific energy for concentration in flotation.

Scenario	Ore grade wt%	Lead, GJ/t-ore	Ore grade wt%	Zinc, GJ/t-ore
Scenario 1 (con. in mine)	4.55	10.85	6.5	50.90
Scenario 4	0.17	51.11	0.24	93.01
Scenario 8	0.002	3,220	0.003	3,579
Scenario 12	2.5×10^{-5}	267,407	3.6×10^{-5}	293,007

from literature review [26, 37, 40, 45, 51, 52], such as recovery ratio, residence time, the volume of the cell, etc.

5.3. Refining process

Refining is the last step to obtain pure metals [53]. In this case, the metals studied are not pure yet, so other processes are used to obtain the corresponding metal bullions. Pyrometallurgy is the treatment chosen for lead refining due to the high velocity of the reactions, the high production, and because it is the most common and developed process for obtaining pure lead [56].

There are several ways to obtain the bullion for the zinc refining process, being ISF (Imperial Smelting Furnace) and electrolysis the most common [36]. Although ISF experimented an important growth at the end of the 90's decade, the electrolytic process is the most applied since 1970, and it is expected to continue as it counts with 86 plants, 76 more than the second one [36].

5.3.1. Lead

There are several procedures to treat lead, being historically the most common based on the two-stage process for primary production [37]. Secondary lead production is derived from scrap and acid batteries due to the high proportion of lead they contain [57]. There is an alternative process to the two-stage process called direct smelting, which has advantages over the conventional treatment (e.g., more efficient process in terms of energy consumption), obtaining a high percentage of lead in the slag [37].

In this study, we consider direct smelting as is the most efficient and simplest process to obtain lead [49]. There are several direct smelting processes (Isasmelt, Kivcet, QSL, Outokumpu), and all of them hold different heat input, designs, and process control procedures [44, 51]. We use the QSL process;

as it proceeds in one single step, the emissions are lower, and the feed range is very wide [49].

Fig. 4 shows the process applied to obtain the lead bullion. As it can be seen, a sintering machine and a blast furnace are the main units of the process. Although it is unnecessary to incorporate the sintering unit, it is useful to remove the pulp's remaining water. Coke is then introduced in the blast furnace as a fuel, limestone is introduced to react with the pulp, and the air is introduced to control the temperature of the blast furnace [44, 51].

The blast furnace outputs are related to the chemical reactions produced in it, achieving lead bullion with a lead grade of 99%, while sulfides mainly form matte. Further, speiss (a mixture of metal arsenides and antimonides) is composed of oxides, and the slag is composed of various metal oxides and a small percentage of lead.

5.3.2. Zinc

As it was already mentioned, pure zinc is obtained through an electrolytic process, which is shown in Fig. 5. This process consists of a roasting step to eliminate the sulphur of the feed and convert it into zinc oxide [36]. The following step is to prepare the solution, which involves different leaching stages. Electrolysis is then applied with a final melting step in a furnace to obtain pure zinc [36].

The feed contains a high amount of sulfides and must be converted into oxides to eliminate the pulp's impurities to prepare it for the following steps [45, 50]. The roasting process's significant impurities are Cu, Pb, Si, Ca, Na and K [58]. This process is carried out through the roasting furnace, where natural gas is introduced in order to react with the pulp and eliminate sulfurs. The oxygen input is controlled avoiding reaching temperatures higher than 960°C to prevent molten phases [58].

Once the feed is almost free of sulfides, it is sent to the leaching unit to dissolve zinc as selectively as possible to create a solution suitable for upcoming

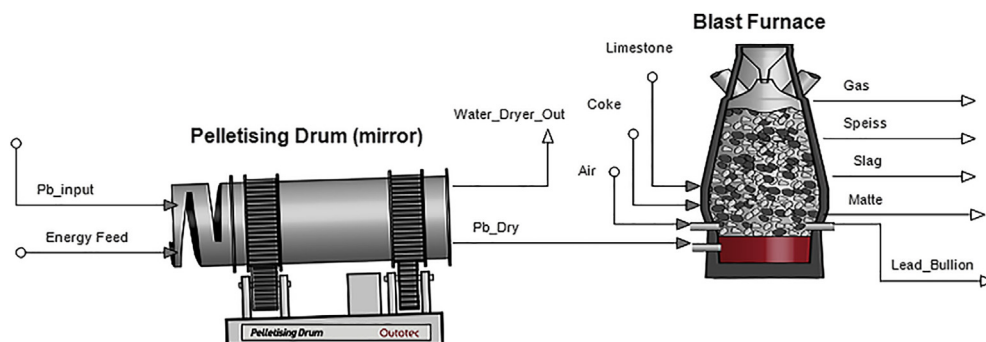


Fig. 4. Lead the refining process.

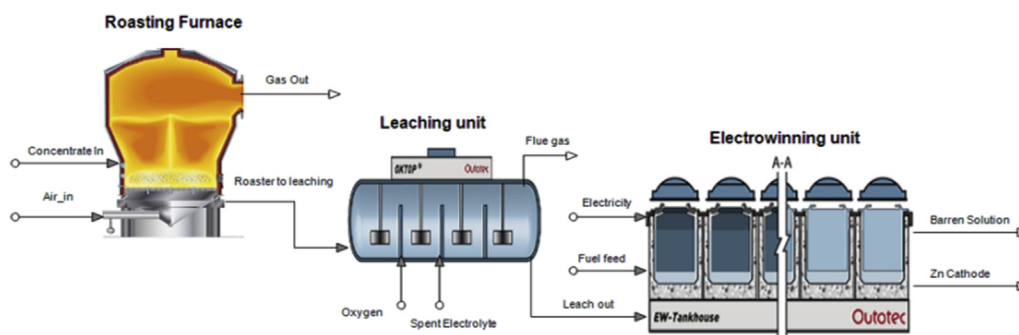


Fig. 5. Zinc refining process.

processes [45, 54]. Apart from other leaching agents, zinc oxide is usually leached by sulfuric acid due to its chemical properties and low cost [59], setting up the leaching rate according to temperature, time, pH, and particle size, among others [54, 55]. Leaching is carried out in two steps: the primary leaching where zinc sulfate and the high amount of zinc oxide will be dissolved by neutral leaching, and secondary leaching where zinc ferrites will be eliminated, although it could be challenging to leach the ferrite [45, 56].

To end up with the refining, the feed is introduced in the electrowinning unit, where zinc ions are discharged from a zinc sulfate solution with an open electrolytic cell [36]. It must be noted that gas treatment has been considered along the refining process. However, due to the low impact in the final results, it has been discarded.

6. Analysis

6.1. Specific concentration energy as a function of ore grade

As explained in the introduction, ore grades are expected to decrease in the future as mines become depleted through the increasing extraction.

Different scenarios were created, reducing the concentration in mines to estimate the corresponding energy consumption. Fig. 6 and Fig. 7 show the results obtained for lead and zinc, respectively. It can be seen that, as expected, the energy increases exponentially when the ore grade of the mine decreases. This can be explained by analyzing the comminution and flotation processes. The comminution process is applied to reduce the particle size with a specific concentration. Therefore, when ore grade declines, the specific comminution energy increases since less desired mineral is contained in the rock processed. On the other hand, the flotation process increases because more roughers, cleaners, and scavengers are needed to concentrate the mineral until typical values before sending it to the metallurgical process. With this concentration, flotation units require a high amount of specific energy since the concentration values must be decreased to a very low ore grade (close to 10^{-5} wt%).

Some authors [61–63] have designed different models trying to identify which is the lowest ore grade from which to extract metals. Some results show that this value is 5×10^{-5} wt-% [35] as an ore grade limit. Below that number, production costs

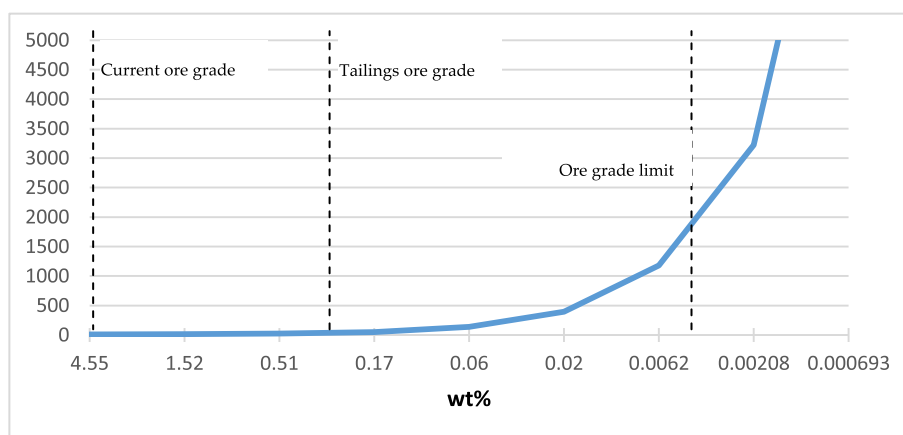


Fig. 6. Specific energy for concentration for lead [G]/t-Pb.

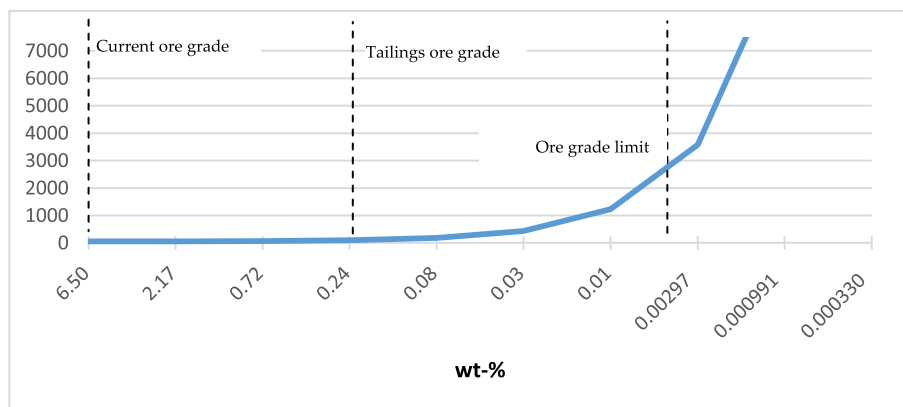


Fig. 7. Specific energy for concentration for zinc [GJ/t-Zn].

would be higher than the value of the ore, considering the best available technologies nowadays [17]. It is known that there are mines with an ore grade close to 0.xxx wt%, but are not economically profitable [62]. Additionally, it is demonstrated by the same authors that the lower the concentration, the smaller the recovery yield, being necessary to do the process many more times since this parameter goes down with small ore grade reductions [61–63].

Nowadays, the specific energy for concentration used for the beneficiation process for lead and zinc is 10.85 GJ/t-Pb and 50.90 GJ/t-Zn, respectively. According to the data obtained along with the study, these values would increase exponentially when the ore grade decreases. Table 4 has been elaborated to put into context the results, comparing the specific energy obtained and the tons of oil equivalent (toe) with meaningful concentrations to understand the order of magnitude that could be reached. The scenarios generated have been created by reducing the concentration one-third at any time until the theoretical limit is reached.

The first scenario has been chosen since it is a typical concentration found in mines, and it is the start point of this study. In this case, obtaining a ton of lead and zinc requires 0.259 toe and 1.22 toe, respectively. Scenario 3 for lead and Scenario 4 for zinc represent a concentration that is in the same order of magnitude that can be found in tailings [28]. It can be seen that obtaining a ton of lead from tailings would require 0.55 toe, which more than

doubles current extraction energies. On the other hand, a ton of zinc would require 2.22 toe, which means an increase of more than 80% of the energy needed from the first scenario.

Scenario 8 is the last comparison since the concentration analyzed for both metals is just after the limit established by Sverdrup et al. [17], which affirms that it is not economically feasible to extract any metal from that concentration. At this point, the energy required to extract a ton of lead would increase to almost 77 toe, while 85.5 toe would be needed to obtain a ton of zinc. In other words, the energy to obtain lead would increase almost 300 times in comparison with the first scenario, while zinc would increase more than 70 times.

As a consequence, and after comparison with previous studies from the literature review, it has been stated that the values obtained are much higher, so the situation is even worse than what other authors thought. It must be mentioned that the procedure followed in this study can be considered more robust than those calculated by [19, 46]. This is because we have precisely modeled all units required to mine in this paper and beneficiate the minerals when ore grade declines. The data obtained is not based on trends but on simulated behaviors of what a real mine would eventually undergo. Thanks to the methodology used in this paper, we have calculated the energy required to extract minerals from tailings, finding a new source affordable in terms of energy and economy.

Table 4. Comparison of the specific energy obtained.

Pb			Zn		
Wt%	GJ/t-Pb	toe/t-Pb	Wt%	GJ/t-Zn	toe/t-Zn
Sc. 1 (4.55)	10.85	0.259	Sc. 1 (6.5)	50.90	1.21
Sc. 4 (0,2)	51.11	1.22	Sc. 4 (0.24)	93	2.22
Sc. 8 (0.00208)	3220	76.91	Sc. 8 (0.00297)	3579	85.5

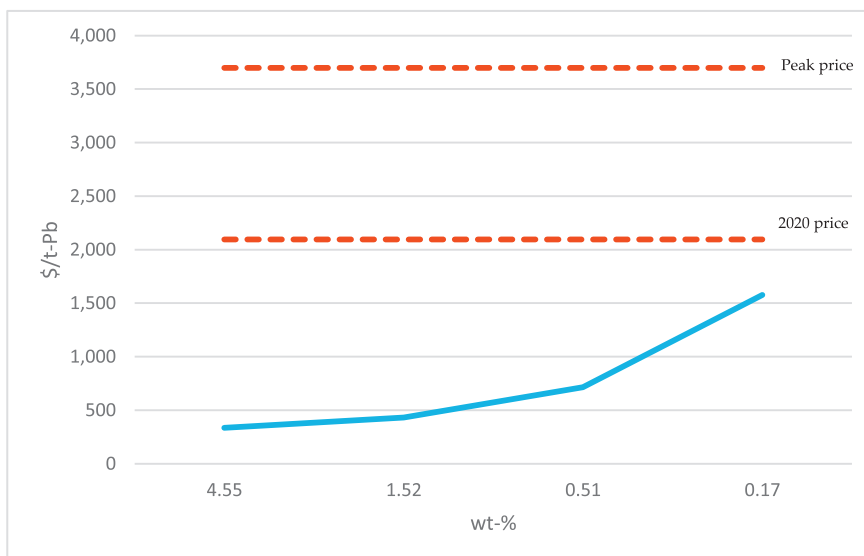


Fig. 8. Lead price range (\$/t-Pb).

6.2. Cost assessment as a function of ore grade

Another analysis has been carried out, focusing on the price of the commodities and the expected value lead and zinc could reach in the future. Even if commodity prices are generated in the market, these should at least cover all associated costs, including energy, water and chemicals used to obtain the refined metal, and leave a profit margin for investors. Additional costs are related to investment, operation and maintenance costs, royalties, etc.

According to our calculations, the energy requirements considering a typical ore grade currently found in mines (4.55 wt%) is about 10.85 GJ/t. We can now transform this energy into monetary prices. To that end, we will consider that such energy is in the form of electricity. It should be mentioned that there are different types of energy involved in the process, such as diesel for waste rock transport, eventually natural gas, etc. Yet by considering that all energy is paid at the electricity price, provides us with an upper bound. Obviously this exercise only intends to provide orders of magnitude because uncertainties are very high. The electricity price chosen is that of the US in year 2020: 0.111 \$/kWh [63].

With the aforementioned values, we can have an estimation of the energy costs associated to an average lead deposit: 335 \$/t. Considering 2020 lead prices (2,095 \$/t), energy costs contribute to about 16% of the price. In short, investment, O&M, royalties, profit, etc. would amount to 1,760 \$/t.

With the models and the scenarios shown before, we can now estimate energy costs as a function of

the ore grade, considering a constant energy price of 0.111 \$/kWh. These are shown in Fig. 8. As ore grades decline, the margin left to other costs and profit significantly reduces. For an ore grade of 0.17 as could be found in tailings, the energy costs would amount to 1,576 \$/t. If the rest of the costs plus the benefit would remain constant and equal to 1,760 \$/t, the tailings price would increase to 3,336 \$/t; which is close to the maximum historical lead price. This means that if commodity prices increased, tailings could eventually become a cost-effective source of lead. Table 5 has been created to spot all the figures mentioned for lead case in every scenario.

These values should be considered as a very rough approximation, because arguably, the other costs will also change when ore grades decline and commodity and electricity prices will fluctuate as well.

This same analysis has been created for zinc (Fig. 9). If energy cost and the rest of costs would remain constant, the maximum price for lead obtained from tailings would increase to 4,153 \$ per t. This value is close to the historical peak, but it is lower, which

Table 5. Comparison of the specific energy obtained.

(\$/t)	Pb		Zn	
	4.55 ^a wt%	0.17 ^b wt%	6.5 ^a wt%	0.24 ^b wt%
Energy costs	334,46	1,576	1,569	2,855
Other costs	1,760	1,760	1,285	1,285
Total	2,095	3,336	2,855	4,153

^a Current ore grade.

^b Tailings ore grade.

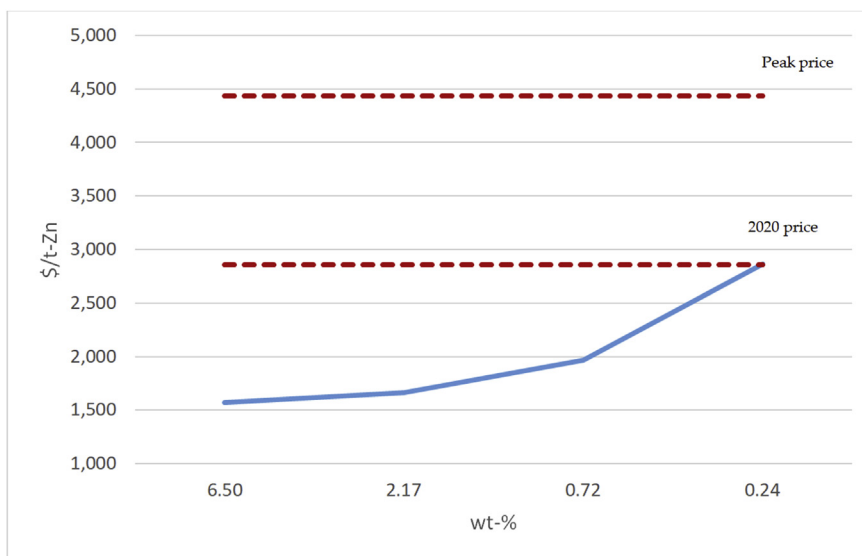


Fig. 9. Zinc price range [\$/t-Zn].

means that at the moment tailings ore grade are reached, the new virtual price for a ton of zinc would remain below the historical peak. Thus, it could be considered as a viable source. Table 5 shows the results for both scenarios.

6.3. Considerations

Mines are composed of different minerals with different concentrations, and an important value of the data obtained is the comminution process. It must be noted that Bond's work index chosen for all the studies is 11 kW h/t [50], as it is typical for mines containing galena and sphalerite. However, this value can differ if the mine's concentration for galena or sphalerite is lower or these minerals are found together with others with a higher Bond index. This parameter is related to the reduction ratio (R_r). Then, it is essential to know the Bond Index of the rock to process because depending on the value applied, the specific energy for any unit of the comminution will be calculated.

Although the comminution process is the same for both metals, the energy allocation cannot be the same due to their properties and the concentration at the beginning of the process. In this way, according to the Ecoinvent Database energy consumption, the percentage assigned to lead and zinc is 37.4% and 62.6%, respectively [65]. Additionally, in the blast furnace (included in the refining process), a value of 31.4 MJ/l [66] has been considered as the High Heating Value (HHV) for carbon. Ore handling is considered for the processes of transportation, storage, feeding, and washing of the ore

on route or during the different stages through the beneficiation process [31, 67], obtaining these data from the literature review [33, 60, 65].

While ore handling data has been taking from the literature review, refining both metals has been compared with other studies and reports [48, 66], obtaining small differences between the results and the bibliography, remaining in the same order of magnitude.

The results obtained show that the specific energy for concentration is higher for zinc than for lead. This could be explained by the cost allocation applied during the comminution process, which can reach more than 90% of the total value in low concentrations. These values could change if the cost allocation were different, thereby reducing the figure obtained. Different studies revealed [68, 69] that the specific energy required to extract zinc would decrease when the energy efficiency improves.

7. Conclusions

Through the methodology applied and HSC software, it has been possible to analyze the behavior of the specific extraction and beneficiation energy of lead-zinc deposits when ore grades decline. Such deposits serve as a proxy of what is likely to happen to the whole mining sector when mines become depleted through a probably accelerated extraction to meet increasingly higher raw material demands. As expected, the trend is not linear but exponential, which implies that much more GHG emissions will be generated as long as

mining relies on fossil fuels. This means that the mining industry will arguably rank first among the most consuming and climate change contributing economic sectors.

Some authors consider that there is no limit to extraction because they trust in technology development. However, it is not possible to know how technology would evolve. In any case, the second law of thermodynamics cannot be overcome: the lower the ore grade, the greater the energy and other resources costs, and the associated environmental impact. Some limits of extraction must be considered. With current technology and the minimum concentration calculated in this paper, extracting a ton of lead and zinc would require 76.91 toe and 85.5 toe, respectively, needing to process millions of tons of ore, which would be, of course, economically unfeasible.

Since the demand is increasing and mines are being exhausted, the production will be reduced, and there will be a moment in time where the demand will be higher than supply. Thus, recycling becomes key. For the lead case, recycling ratio is higher than the 60%, which can be considered a high number in comparison with other metals. On the other hand, unfortunately, recycling ratio for zinc is around 15%, still far from an ideal figure (considering that 100% recycling is impossible to reach). In any case, more research must be carried out to try to increase recycling ratios to provide more share in the market and avoid the total depletion of mines.

Decreasing ore grades opens the opportunity to new extraction sources other than mineral deposits. As it has been seen in the paper, demand could be eventually supplied extracting minerals from tailings. However, this would entail that the energy would be multiplied by more than five times in the case of lead and almost two times in the case of zinc. Consequently, more emissions would be released into the atmosphere, even if this would preserve new unexplored regions and ecosystems to be potentially altered through mining. That said, the cost assessment carried out indicates that for both commodities, even if processing costs increase, there is still margin for profit. This is because the new costs assuming that O&M, investment costs, royalties and profit remain constant would all together remain below the maximum historical commodity's price peak. In summary, obtaining minerals from tailings would be arguably cost effective.

Another opportunity that opens up is what is called landfill mining. Many devices containing a

high amount of minerals are sent to landfills, provoking serious environmental damage. As such, the concentration of many strategic materials in landfills is increasing year by year, even exceeding that of natural deposits. Landfill mining could become an important source of materials in the near future. That said, as long as consumption grows, relying on secondary materials will not be enough to satisfy the whole demand and natural mining will still be required.

Conflicts of interest

None declared.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

This paper has received funding from the Spanish Ministry of Economy and competitiveness (ENE2017-85224R).

Acknowledgments

Thanks as well to Ivan Fernandes of Helmholtz Institute Freiberg for Resource Technology for the revision of the first versions of this paper.

References

- [1] Charles V, Linda S. Human Behavior and Environmental Sustainability: Problems, Driving Forces, and Research Topics. *J Soc Issues* 2007;63(1):1–19.
- [2] Ikhlayel M. An integrated approach to establish e-waste management systems for developing countries. *J Clean Prod* 2018;170:119–30.
- [3] Hischier R, Wa P, Gaughhofer J. “Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). *Environ Impact Assess Rev* 2005;25:525–39.
- [4] Calvo G, Valero AA, Valero AA. Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe. *J Ind Ecol* 2017;22(4):839–52.
- [5] Calvo G, Mudd G, Valero A, Valero A. Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources* 2016;5(4):36.
- [6] Camizuli E, et al. Trace metals from historical mining sites and past metallurgical activity remain bioavailable to wildlife today. *Sci Rep* 2018;8(34–36):1–11.
- [7] Viederman S, A Sustainable Society “. What Is It? How Do We Get There? *The George Wright Forum* 1993;10(4):34–47. New York.
- [8] Jose-Luis P, et al. The energy needed to concentrate minerals from common rocks: The case of copper ore. *Energy* 2019; 181(August):494–503.

- [9] Northey S, Mohr S, Mudd GM, Weng Z, Giurco D. Modeling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resour Conserv Recycl* 2014;83:190–201.
- [10] Christie T, Brathwaite B. “Mineral Commodity Report 6 — Lead and Zinc. New Zeal Min 1995;16:22–30.
- [11] Thornton I, Rautiu R, Brush SM. “Lead: The facts. Properties of Lead,” *Lead Facts*. 2001. p. 6–14.
- [12] Gregurek D, Peng Z, Wenzl C. Lead and Zinc Metallurgy. *Jom* 2015;67(9):1986–7.
- [13] ILZSG. International Lead and Zinc Study Group. Press Release Int Organ 2018;April:4.
- [14] Bernhardt D, Reilly II JF. USGS: Mineral Commodity Summaries. 2019.
- [15] Garside M. Major countries in lead mine production worldwide from 2010 to 2019 [Online]. Available: February, 2020. <https://www.statista.com/>. [Accessed 2 April 2020].
- [16] Mohr S, Giurco D, Retamal M, Mason L, Mudd G. Global Projection of Lead-Zinc Supply from Known Resources. *Resources* 2018;7(1):17.
- [17] Sverdrup H, Ragnarsdottir KV. Natural resources in a planetary perspective. no. 2 *Geochemical Perspect* 2014;vol. 3:129–341.
- [18] Anyadike N. Zinc Recycling. vol. Zinc essen Int Zinc Assoc 2011:2.
- [19] Garside M. Major countries in worldwide zinc mine production from 2010 to 2019 [Online]. Available: February, 2020. <https://www.statista.com/>. [Accessed 2 April 2020].
- [20] Abadías A, et al. Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production. September 2018 *Miner Eng* 2019;131:51–65.
- [21] Palacios JL, Abadías A, Valero A, Valero A, Reuter MA. Producing metals from common rocks: The case of gold. *Resour Conserv Recycl* 2019;148(April):23–35.
- [22] Palacios JL, Fernandes I, Abadías A, Valero A, Valero A, Reuter MA. Avoided energy cost of producing minerals: The case of iron ore. *Energy Reports* 2019;5:364–74.
- [23] Arribas A, Moro C. Mineralizaciones españolas de Pb-Zn asociadas a fenómenos cársticos en rocas triásicas y jurásicas. October 11th *Studia Geológica Salmant* 1985;XXI:125–51.
- [24] Vicencio C, Alday R, Rojas R, Pizarro N, Soublette A. “Zinc y Plomo,” Chile, Universidad Católica del Norte. Facultad de Ingeniería y Ciencias Geológicas. Departamento de Ingeniería y Sistemas de Computación; 2008.
- [25] Outotec. Outotec HSC chemistry software [Online]. Available: 2020. <https://www.outotec.com/>. [Accessed 4 December 2019].
- [26] Arne D, Geo P, McGarry L, Geo P, McGarry L. “NI 43-101 Technical Report on the Macmillan Pass Zinc-Lead-Silver Project, Watson Lake and Mayo Mining Districts. Yukon Territory: Canada; 2018.
- [27] Maynard R, et al. Technical Report for the Platosa Silver-Lead-Zinc Mine, Mexico. 2018. p. 150.
- [28] Stephenson PR, Smith HA, Riles A, Molavi M. Technical Report for Ying Gold- Silver-Lead-Zinc Property, Henan Province, China June. *AMC Min. Consult. LTd*; 2012. p. 221.
- [29] Metso. Basics in minerals processing. 10th ed. Metso Corporation; 2015.
- [30] Rankin W. Minerals, Metals and Sustainability. In: *Meeting Future Material Needs*; 2011.
- [31] Napier-Munn T, Barry A W. *Mineral Processing Technology. An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*. October. 2006.
- [32] Graf GG. “Zinc Ullmann's encyclopedia. *Encycl Ind Chem* 2005:23.
- [33] Sutherland CA, Milner EF, Kerby RC, Herbert T, Melin A, Bolt HM. “Lead Ullmann's encyclopedia. *Encycl Ind Chem* 2006:48.
- [34] Valero A, Valero A. *Thanatia: the destiny of the Earth's mineral resources*. Zaragoza: World Scientific Publishing; 2014.
- [35] Lenzen M. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Convers Manag* 2008; 49(8):2178–99.
- [36] Sinclair RJ. The Extractive Metallurgy of Zinc. *Australas Inst Min Metall* 2005;13:297.
- [37] Thornton I, Rautiu R, Brush S. “Lead industry profile,” *Lead Facts*. Chapter 4. 2001. p. 47–70.
- [38] Flores Briceño R, Castillo Espinosa JR. Flotación de Plomo Y Zinc, Universidad Nacional Jose Faustino Sanchez Carrion, Perú, Ingeniería Química y Metalurgia. *Concentración de Minerales II* 2013.
- [39] Valero A, Valero A. “Exergy of comminution and the Thanatia Earth's model. *Energy* 2012;44(1):1085–93.
- [40] Skarin OI, Tikhonov NO. Calculation of the Required Semi-autogenous Mill Power based on the Bond Work Indexes. *Eurasian Min* 2015;1:5–8. Technology and technic of ore preparation processes.
- [41] Rowland C, Kjos D. Rod and ball mills, *Mineral Processing Plant Design*. New York: AIMME; 1978.
- [42] King RP. Modeling and simulation of mineral processing systems. UTAH: Reed Educational and Professional Publishing Ltd A; 2001.
- [43] Rowland CA. Using the Bond work index to measure operating comminution efficiency. *Miner Metall Process* 1999; 15(4):32–6.
- [44] Luo B, et al. Characterization of sulfide film on smithsonite surface during sulfidation processing and its response to flotation performance. *Powder Technol* 2019;351:144–52.
- [45] Shardt YAW, Brooks K. Automated System Identification in Mineral Processing Industries: A Case Study using the Zinc Flotation Cell. *IFAC-PapersOnLine* 2018;51(18):132–7.
- [46] Krolak T, Palmer K, Lacouture B, Paley N. NI 43-101 Technical Report. Alaska, USA: Red Dog Mine; 2017. Anchorage, AK USA.
- [47] Dunne RC, Lane GS, Richmond GD, Dioses J. Interpretation of flotation data for the design of process plants. *Australas Inst Min Metall* 2002;(January):28.
- [48] Sinclair RJ. Chapter 7. Direct Smelting processes. In: *The Extractive Metallurgy of Lead*. 15. *Australas. Inst. Min. Metall*; 2009. p. 99–127.
- [49] Michaud D. “Table of Bond Work Index by Minerals,” *911 Metallurgist* [Online]. Available: 2015. <https://www.911metallurgist.com/blog/table-of-bond-work-index-by-minerals>. [Accessed 19 June 2015].
- [50] Siemens AG. Maximum productivity with maximum safety. 2016. p. 16. www.siemens.com/mining, no. VRMI-B10009-00-7600.
- [51] Atchireddi S, Faria E. Achievement of high energy efficiency in grinding mills at Santa Rita. no. January. In: *45th Annu. Meet. Can. Miner. Process*. 22–24; 2013. p. 97–110.
- [52] Sehlotho N, Sindane Z, Bryson M, Lindvelt L, Sehlotho L. Flowsheet development for selective Cu-Pb-Zn recovery at Rosh Pinah concentrator. *Miner Eng Jun*. 2018;122:10–6.
- [53] Sinclair RJ. Chapter 16. Energy Consumption. In: *The Extractive Metallurgy of Lead*. vol. 15; 2009. p. 259–68.
- [54] Outotec, “OUTOTEC FLOTATION TANKCELL® e-SERIES BENEFITS,” Sustainable use of Earth's natural resources. 2016. p. 4.
- [55] Bustamante Rua MO, Restrepo Baena ÓJ, Gaviria Cartagena AC. *Piometalurgia*. Univ Nac Colomb 2008:109. Programa a.
- [56] Berdowski J, et al. “Lead production,” *EMEP/EEA Emiss. Invent Guideb* 2009 2009:24.
- [57] Nyberg J, Kortela U, Jämsä-Jounela S-L, Ylinen R. Characterisation and control of the zinc roasting process. *Faculty of Technology, Oulu University*; 2004.
- [58] Napo D, Ntuli F, Muzenda E, Mollagee M. Process Intensification of Zinc Oxide Leaching Process Using Sulphuric Acid. *Lect Notes Eng Comput Sci* 2011;2(2194): 623–7.

- [60] Gupta TK, Mukherjee CK. Hydrometallurgy in Extraction Processes, Volume II vol. 2. CRC Press; 1990. p. 39–78.
- [61] Nayak S, Charan Sabat K. Principles of extractive metallurgy. vol. 3rd semest, no. Lectures note Dep Metall Mater Eng Parala Maharaja Eng Coll Berhampur 2009:98.
- [62] Prior T, Daly J, Mason L, Giurco D. Resourcing the future: Using foresight in resource governance. *Geoforum* 2013;44: 316–28.
- [63] [Online]. Available: USA electricity prices. Electricity prices for households; 2020. <https://www.globalpetrolprices.com/>. [Accessed 26 February 2021].
- [64] Dones R, et al. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. *Swiss Cent. Life Cycle Invent.* 2007;2(5): 185.
- [65] Poder calorífico (q) de diversas sustancias Producto,” *Minist. Trab. y asuntos Soc.*, no. Instituto Nacional de seguridad e higiene en el trabajo, p. 3.
- [66] Hofstrand. Liquid Fuel Measurements and Conversions. *Ag Decis Maker Iowa State Univ* 2008;C6-87:4. October.
- [67] Qi C, Ye L, Ma X, Yang D, Hong J. Life cycle assessment of the hydrometallurgical zinc production chain in China. *J Clean Prod* 2017;156:451–8.
- [68] Norgate TE, Jahanshahi S, Rankin WJ. Assessing the environmental impact of metal production processes. *J Clean Prod* 2007;15(8–9):838–48.