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A new way to assess the loss of mineral wealth: the case of copper

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Abstract:

The search for new electronic appliances, the urgent need for renewable energy technologies and on the multiple uses in the society have produced a high demand for metals. The copper claim has increased significantly in the last centuries. Chile is the world´s largest copper producer. However, the higher production of copper has been accompanied by a considerable decay of ore grades in the Chilean copper mines. That is why it is required to appropriately assess the loss of mineral (LMW) wealth. Methodologies to determine the LMW based on the second law of thermodynamics and the Exergy, have provided valuable information on the scarcity of minerals. The methodology proposed in this paper is based on the simulation of mineral processes for the concentration of copper using HSC from an average mineral composition of the leading in some mines in Chile. One approach to estimating LMW has been utilising the exergy replacement cost (ERC). Although this procedure has been effective in establishing an ultimate scenario of mineral depletion, named Thanatia, it needs to correlate appropriately with the current market conditions to develop a framework for a fairer scheme for the prices of metals. In this paper is proposed a new approach to estimate LMW for the case of copper.

Keywords:

exergy replacement cost (ERC), metal demand, copper, mineral depletion, Exergia

1. Introduction

The transition towards a more sustainable society requires more clean energy technologies, therefore, more minerals and metals are needed. A report of the International Energy Agency [1], it was highlighted the importance of such minerals. Some of them, are categorized as critical for some clean energy technologies. In this report, it is pointed out that the rise of demand for copper and rare earths to more than 40% in the next two decades.

Authors such as Mudd [2]–[6], Craig et. al [7] and Norgate [8] have mentioned the issue of the decline of ore grade in mines over time. In a research [9], the peak production of copper is estimated from 2031 to 2042. A study by Calvo et al. [9] investigated the reduction of ore grades in 25 mines in Chile, Australia, and Peru. The production of these mines accounted for 32% of the total copper production at that time. In addition to this, it was also observed a 25% reduction in average of the ore grade from 2003 to 2013. The decrease in the concentration of copper in mines produced an increase in 46% in energy consumption. On one side, more metals are required, but on the other rich metal deposits have been already extracted. Therefore, the supply of cooper for the next generations is compromised to actions that must be taken for sustainable production in present generations.

In 2020, China had 33,2% of the global share of copper production, and Chile 20,5%. This country had a robust worldwide industry of copper with an essential impact in its economy. In 2020, the share of the copper industry in Chile accounted for 11,2% of its Gross Domestic Product (GDP) [10].

In Chile, the decline of ore grade has been also notorious (Figure 1). The average ore grade in the copper mines was about 1.4% in 1999, which decreased to about 0,6% in 2018.

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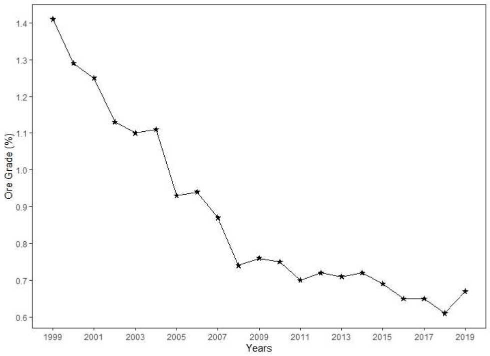

Figure 1. Decline of the average ore-grade of copper mines in Chile.(Calculated based on:[11], [12])

The need for more metals will also produce more extraction of minerals in countries, for example, Chile, where the rich deposits have been already extracted as shown in Figure 1. This will also cause a rapid loss of mineral depletion. It is important to know that mineral endowment was defined by Harris and Agterberg [13] as the amount of metals in a given region. This accumulation of minerals, traded later as commodities, means abundance for a country. Because of the growing need for minerals, they are extensively extracted, producing a loss of mineral wealth (LMW). The LMW represents a quantitative indicator of mineral depletion in that country [6] [37] [38].

As can be seen, it is crucial to have an approach to estimate the LMW. In a publication [17], in this paper is used the exergy replacement cost (ERC) concept to estimate the loss of mineral extraction in 22 countries in Latin America. In this investigation, it was used values of ERC previously reported in [18]. The concept of ERC and its methodological approach will be reviewed in the next section. Nevertheless, this value of ERC for copper will provide a certain sense of the importance of mineral depletion; it fails to give some hints towards a fairer price of minerals.

This paper will provide a new approach based on simulation with HSC Chemistry 9 and HSC Sim software [19] to estimate a new value of ERC for copper as a valuable indicator to evaluate mineral depletion more appropriately.

1.1 The concept of the exergy replacement cost

The traditional way to value minerals has been through the market price. However, prices fluctuate and are unstable because they depend on many factors [19]. Therefore, prices are not sufficient to give an appropriate value to minerals. The mass has been another approach to valuing minerals. Nevertheless, they do not consider the geological scarcity or the difficulty of the production process. An alternative method is using the concept of the exergy replacement cost, which stands for ERC. This concept has its basis on Exergy. For fossil fuels, when they are burned the liberation of energy is accompanied with their higher heating value (HHV) [20], [21].On the other hand, non-fuel minerals are not combustible the HHV is no longer valid. The use of exergy for non-fuel minerals has two perspectives; a traditional way to treat them has been using their chemical exergy. On this perspective, Szargut has published chemical exergy of different elements [22]. These values have been used by Ayres [23], Dewulf et al. [24] and Szargut et al. [15], [25], [26] to evaluate mineral resources. However, this perspective is not valid to allocate the fair value of minerals. A study [28] clearly pointed out the fact by showing that the chemical exergy of precious metal gold is 60 kJ/mol is considerably lower than aluminium 796 kJ/mol. Exergo- ecology, a discipline postulated by Valero [27], can give a more appropriate scheme to value minerals. Physical Geonomics, one Exergoecology´s division, deals with the application of exergy to assess non-fuel minerals. The exergy of minerals has two components: one is related to chemical composition (chemical exergy) and the other is associated with the relative concentration in the Earth´s crust (concentration exergy). The latter makes minerals more valuable than the former. Nature provides a “free bonus” or in economic terms a “hidden cost” just for having minerals concentrated in mines and not dispersed throughout the Earth´s crust. This “free bonus” significantly reduces the costs associated with mining processes. When higher-ore grade mines become depleted, a reduction in this free bonus occurs, leading to an extensive exergy consumption to extract a similar quantity of metal. The bonus provided by nature can be measured through the ERC.

ERC is postulated as the energy that would be required to extract and concentrate a mineral from a completely dispersed state at a crustal concentration (xc) to the conditions of concentration and composition found in the mine (xm) by using available technology. Thanatia represents a state of total mineral dispersion into the Earth´s crust. Thanatia´s composition is made up of 324 species, 292 minerals and 32 diadochic elements included in the crystal structure of other elements [28], [29].

The exergy required to concentrate minerals from a concentration found in Thanatia (xc) to the average concentration (xm) for different minerals can be found in [18]. This research, will be focused to the ERC for copper. To estimate the ERC for copper, Valero et. al assumed the concentration of copper in the Earth´s crust xc = 6.64x10-5 g/g [30] which corresponds to 0.006 wt-%. Also, an average ore grade assumed xm = 1.67x10-2 (0.5 wt-%) [31]. The ERC for copper reported in [18] was 292 GJ/t-Cu. They considered that 60% of the total energy was for the mining and concentration [32].

1.2 The need of a new approach

The ERC of different minerals were calculated by Valero et al. [32] by observing the behaviour of the decrease of ore grade and increase in energy consumption for some metals, such as cobalt, copper, gold, nickel, and uranium. Valero et al. proposed a function that portrayed the relationship between the energy consumption as a function of the ore grade, Equation (1).

$$E_{(X_m)} = A \, . X_m^{-0.5} \tag{1}$$

Where $E_{(X_m)}$ is the energy for the concentration and extraction of minerals at the ore grade (xm), and the coefficient A is determined for each mineral.

In [33] the LMW was estimated for a series of mineral produced in 22 countries in Latin America by using conventional ERC. A remarkable result of this investigation was market prices do not compensate the LMW in the region. As forthcoming, it was established the need to have a scheme to estimate fairer prices for minerals.

The methodology proposed to estimate ERC is limited to the experience of observing historical data of some metals. In this approach, as reported in [34] geological principles prevailed over metallurgical considerations.

An upgrade to the ERC for iron, copper and gold based on simulations of a specialized software HSC Chemestry [35] by considering mineral processing was reported in [36], [37], [38], respectively. These new values of ERC varied in orders of magnitude to the previous ones conveyed in [18]. They differ in the method of calculation from observation to simulation in HSC.

Previous ERC [18] and new ERC for iron, copper and gold [36], [37], [38] are higher values in GJ/t that would lead to numerous errors to estimate a fairer price of minerals. The reason for such magnitude of values is that Thanatia is used as starting point to determine the ERC. Therefore, a new approach is required to have an intermediate scenario that provides more appropriate ERC in this copper case.

This research will be focused to establish this intermediate scenario, which will be described in the next section.

1.3 An intermediate scenario for a new ERC for copper

In order to establish a scenario, first, it is presented an ideal scenario of mineral dispersion in which all minerals are diluted through the Earth´s crust total mineral dispersion named Thanatia. On the other hand, it is described the cut-off grade as the minimum grade in a deposit in which a metal can be economically extracted [39], [40]. Therefore, an intermediate scenario can be found between the concentration of copper in Thanatia and the cut-off grade. In Figure 2, the exergy needed for the concentration of metals is presented as function of the ore grade [28], XB represents the concentration of metal at the beneficiation process (c.a. 99 wt-%), XM the ore grade in mines, for instance, the average ore grade in copper deposits is 0.5 wt-%. Then as the ore-grade decreases, the exergy rises exponentially, Xcut-off the cut-off grade at which the extraction of minerals in deposits is not economically viable. We will consider the cut-off grade for Chile. This value was estimated as average value of 0.2 wt-% of copper [41], [42], [43]. Afterwards, XC is the concentration of metal. As written in section 1.1, in Thanatia de concentration of copper corresponds to 0.006 wt-%. The intermediate scenario (Xin.) of analysis for the new ERC for copper is located between a concentration XC and Xcut-off. For the cut-off grade, since our objective is to estimate a new ERC for copper, we choose Xin for copper at a composition of copper of 0.02 wt-%.

Mine La Escondida, in 2020, produced 30% of the total copper production in Chile [10]. Hence, the model in this paper, will be taken a similar mineral composition to La Escondida as input. A literature review was performed, and the most representative minerals were identified. The most predominant mineralogical composition was based on copper sulphides [44] accompanied by a series of minerals, mostly silicates, as is shown in Table 1.

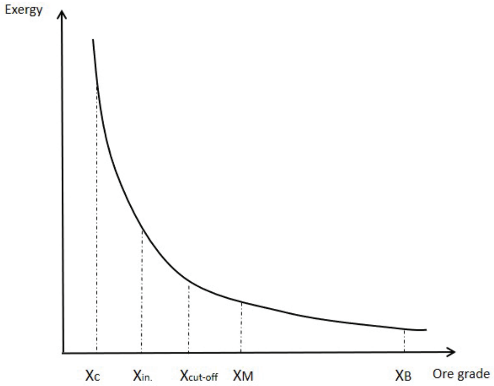

Figure 2. Description of the intermediate scenario for the new ERC for copper.

Estimations were performed on the basis of the abundance of the deposits La Escondida reported in [45], [46]. It was also considered QEMSCAN analysis developed by [47] and [48]. For the model it was allocated each mineral for an average ore-grade of 0.02 wt-% Cu.

2. Methodology

In this section, the stages of determining the new ERC for copper based on HSC Sim 9 [35] are explained.

The target of the model is to estimate the specific energy needed to concentrate copper, in this copper known as the new ERC for copper, from a concentration of copper in the intermediate scenario (0.002 wt-% Cu) to an average concentration in mines (0.5 wt-% Cu). The model was developed to concentrate copper mainly from sulphides, specially Chalcopyrite. Also, the model takes some procedures for the layout reported in previous work to determine ERC from Thanatia [37].

Prior to the model, a literature review was performed [8], [40], as well as state-of-the-art technologies for copper concentration [51]. On the basis of the analysis of operating data for concentrators of copper in La Escondida [57], a flow rate of 6 500 tons per hour was chosen. A top size in the ore feed of 6 E5 µm was considered for the feed.

The new ERC will also consider the energy for ore handling and the concentration of copper. For the ore-handling, it was assumed a minimum distance from an open pit mine to the concentrator so that the fuel consumption per ton of ore prevailed over the distance. For this task, it was supposed a fuel consumption of 0.6 L/ton of rock taken from [58].

The comminution circuit was modelled by following guiding principles reported in [59]. It consisted of three circuits primary crushing, grinding and regrinding. A jaw crusher reduced the 80% of feed particle size (F80) to P80, equal to 10 000 um. Then semi-autogenous (SAG) crushed the rock to 2 000 um Afterwards, a screen is used to separate the oversized particles. The latter went to a pebble mill, where they were reduced to 1 500 um.

During comminution, a fundamental equation to calculate the specific energy required for the mills is Bond´s equation [39], [60] Eq. (2):

$$W = 10\, W_i \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) EF_x \qquad (2)$$

where W is the specific energy consumption of the mill (kWh/t), Wi represents the work index (kWh/t), P80 and F80 are the product and feed passing sizes, respectively measured in µm. The last term, EFx is the product of the Rowland efficiency factors, which depend upon mill, size and type of media, type of grinding circuit, etc. [39], [60]–[63]. Then, the theoretical power draw by the mill (kW) is calculated by W x T, where T is the throughput tonnage (t/h) [39].

A hydrocyclone separated the fines to the flotation circuit with F80 lower than 130 um. The coarse of the hydrocyclone went directly into a ball mill that reduced the oversized particles to 600 um. The flotation circuit mainly separated the higher-copper minerals (sulphides), especially Chalcopyrite. To do this, fast kinetics constants (kf) were set up for Chalcopyrite in the range of 1 to 2.5. These figures were in harmony with values reported in [64] and [65].

The volume and number of cells for the flotation tanks, roughers and scavengers, were established based on data reported by Weiss [51], and Wills and Finch [39].

3. Results and Analysis

The results of the simulations are described in this section. In addition to this, outputs of the model were validated through a comparison between parameters of the comminution and flotation processes with the respective ones found in the literature. As a final point, based on the methodology previously defined in the later section, the specific energy for the concentration of copper from an intermediate scenario (in.) between Thanatia and the cut-off grade, the new ERC for copper is identified.

3.1 Simulation results

From the model, the results were particle size for feed (F80) and output (P80) of the crushers and mills for the comminution processes, Table 1. The reduction ratio (Rr) is calculated by dividing F80 to P80 for every mill. Furthermore, the total reduction ratio is the product of Rr for every mill as specified in [52].

Table 1. Feed and product size, F80 and P80, respectively for the comminution process.

Stage	Equipment	F80 (μm)	P80 (μm)	Reduction ratio (Rr)
Crushing	Primary crusher	15302	10000	2
	SAG mill	4374	2000	2
Grinding	Pebble mill	2968	1500	1
	Ball mill	750	600	2
Re-grinding	HIG mill	131	34	4

The Rr for our model was 32 after the comminution process comes the flotation, which main results of retention time and power consumption are shown in .
Table ***2***.

Table 2. Retention time and power consumption for the flotation process.

Stage	Retention time (min)	Power (kW)
Rougher	14	2250
Scavenger	10	1850
Cleaner	9	185
Scavenger	14	55
Re-cleaner 1	13	75
Scavenger	18	90
Re-cleaner 2	7	150

The outcome of the flotation process had a mass flow rate of 210.10 t/h with a concentration of copper of 0.462%. For the flotation process, the recovery of copper was about 92%, followed by gold 46% and silver 39%.

3.2 Validation of the model

The validation consisted of the comparison between the main results of the model, particularly for comminution and flotation with those reported in the literature. In this sense, for comminution

For the flotation, the parameter for validation was the retention time in flotation. In [51, Ch. 10] the retention time for the roughing circuit was in the range of 13 to 16 minutes. In comparison to the values of our model, they are in the range except for the Cleaner and Re-cleaner 2. They are relatively smaller, nevertheless not so far from the values reported in the literature.

An essential parameter for the validation of the model was final metal recovery. Haque et al. [66] modelled pyro and hydrometallurgical for low-grade copper deposits. In this publication, the recovery of copper was assumed to have a yield between 86% to 89%. The recovery obtained from our model was about 92%. This figure agrees with the previous values reported in the literature. With this comparison, we can see that our model delivers logical and reliable results.

3.3 The new ERC for copper

The energy for comminution depends on the Bond´s work index (Wi), as it was explained in Section 2. In order to have a value that would be used as a reference for faired prices for copper, only one value of the new ERC will be required. Therefore, we assumed an average representative value for Wi equal to 14 kWh/t. This value was in agreement with models for copper in [67].

With these considerations, the power demand for the comminution and the flotation processes was estimated Table 3 .

Table 3. Power draw for comminution and concentration processes.

Stage	Power Demand (MW)	Power Demand (%)
Crushing	10.1	4.3
Grinding	21.3	90.3
Re-grinding	8.2	3.5
Concentration	4.7	2.0
TOTAL	236	100

As can be seen in Table 3, most of the power demand is mostly concentrated in the comminution process (94% approx.). The grinding circuit was the largest consumer.

The specific energy for the concentration process was calculated by following the methodology previously explained, Table 4.

Table 4. Specific energy to concentrate copper from an intermediate scenario.

	Cu concentration (wt-%)	Flow rate (t/h)	Specific Energy (kWh/t)	Specific Energy (MJ/t)
Feed Ore	0.036	6500	36	131
Conc. metal	0.462	220.10	1074	3867

By making a comparison of the average concentration of energy per ton of ore reported for different mines in [58], it can be seen that the value of 36 kWh/t-ore is in the range of those reported for mines such as La Escondida, Michila, Salvador [58]. This also supports that our model delivers reliable results.

In addition to the values of the specific energy shown in Table 5, the ore-handling must be added. For that, a value of 1.2 litres of diesel per ton of rock was considered for the specific fuel consumption. This was reported in [58] as an average value for the energy consumption in the Chuquicamata open-pit mine. The new ERC from the intermediate scenario is shown in Table 5.

Table 5. Specific energy for the concentration of copper from an intermediate scenario in GJ per ton of element.

Phase	Specific Energy (GJ/t)
Ore handling	128
Concentration	3.87
TOTAL	131.87

As can be seen, most of the energy is spent on the transportation of the ore to the concentrator. It is explained because a low ore grade ore (Table 1) is transported.

In Table 6, is made a comparison among values of the exergy replacement cost (ERC) for copper from Thanatia reported in [18]. Also values are compared of ERC based on HSC simulation, considering the starting point Thanatia in [37]. In addition, also is compared the average energy intensity for the Chuquicamata mine from 2000 to 2013, published in [58]. Then it was converted into GJ per ton of copper. Then with this and the exergy replacement cost (ERC) for copper reported in [18], a comparison with the specific energy of the current paper was done, Table 6.

The new ERC for copper is between the ERC from Thanatia in [18] and the specific energy for Chuquicamata [58], Table 8. The new ERC is more than three times the specific energy for Chuquicamata and almost a half of the previous ERC from Thanatia [18]. With regard to the values of

ERC for copper from Thanatia, also based on models in HSC, reported in [37], they differ by one to two orders of magnitude.

Table 6. Comparison of the specific energy of the current work with other reported values in GJ per ton of element.

	Ore	Specific Energy (GJ/t-Cu)	Source
New ERC	Intermediate scenario ($X_{in.}$)	132	current work
Based on HSC-model	Thanatia (X_C)	3100 - 30890	[37]
ERC	Thanatia (X_C)	292	[18]
Chuquicamata		42	[58]

4. Conclusions

More metals are needed to conduct a more sustainable energy transition through renewable energy technologies. The growing need for metal has produced that rich deposits have been exploited. The fact of the mineral exploitation should also be a concern in this path towards a decarbonisation of the society. In this regard, it is vital to have reliable means for the assessment of minerals. One non-conventional way to do this is by applying the concept of the exergy replacement cost (ERC). As a concept ERC has revealed its strengths compared to traditional methods, such as market-price and mass balance. Nevertheless, previous approximations to calculate the ERC for metals do not provide values that can be useful when calculating a market price of metals that consider aspects of mineral depletion. In this regard, the present work is novel in considering an intermediate scenario to estimate a new ERC for a metal widely used and key for an energy transition, copper. In this research, it has been considered an intermediate scenario, one that is located between an approach of total mineral depletion, Thanatia, and the scenario when economic feasibility for the exploitation of metals is not viable, the cut-off ore grade. This research considered the mineralogical composition of a representative copper mine in Chile, La Escondida, as key to developing the intermediate scenario.

The method of calculation of this new ERC for cooper has been based on the use of a reliable software HSC Sim 10.0.7.9 software [35]. This software has been helpful to develop new procedures to estimate ERC a more rigorous approach with mining considerations, as reported in [38].

The new ERC for copper from an intermediate scenario is an appropriate indicator for mineral depletion. It can be helpful to be considered a key indicator of mineral degradation towards the estimation of a fairer scheme for prices. In this scheme is required to have a clear picture on what parameters are the real drives for market prices. They should take into account the more need for energy to extract metals in the near future, as well as the loss of mineral wealth.

A key message of this and previous publications points out the need to give more importance to esteeming current copper deposits, particularly those located in South America. These countries should re-examine their significance as crucial mineral suppliers, particularly when discussing an energy transition.

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