Minerals Engineering 200 (2023) 108150

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Limit of recovery: How future evolution of ore grades could influence energy consumption and prices for Nickel, Cobalt, and PGMs

Ricardo Magdalena *, Alicia Valero, Guiomar Calvo

Research Centre for Energy Resources and Consumption (CIRCE) - Universidad de Zaragoza, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain

ARTICLE INFO

Keywords:
Nickel
Cobalt
PGMs
Tailings
Ore grade decline
Specific Energy
Mineral processing

ABSTRACT

The unique properties of certain metals have made them indispensable in manufacturing advanced technological devices and for use in the green economy. However, these metals are not infinite, and the average ore grades in mines have been decreasing in recent decades. This study examines energy consumption as a function of ore grade decline for Nickel, Cobalt, and platinum group metals (PGMs), using simulations created with HSC Chemistry software. A limit of recovery (LOR) for each commodity was also defined. A comparative analysis of the evolution of ore grades, energy costs, and market prices was additionally carried out. According to the simulations, extracting nickel from sulfide ore tailings would be profitable if the price doubled. As for Cobalt, it would only be feasible if the market price increased considerably. For PGMs, even if the ore grade reached the LOR, it would still be profitable to recover them under certain circumstances explored in the paper.

1. Introduction

Nickel (Ni), cobalt (Co), and platinum group metals (PGMs) are highly valuable due to their diverse range of applications and significant role in the green economy (F. K. Crundwell et al., 2011). They provide specific technical details that are necessary to manufacture better and more efficient devices (Magistretti et al., 2020; Parasuraman, 2000; Wäger et al., 2011). Ni and Co are used in batteries, catalysts, medicines, and permanent magnets (Bao et al., 2019; Cárdenas-Triviño et al., 2017; Fernandes et al., 2013; Orefice et al., 2019), while PGMs are extensively used in catalyzers and catalytic converters of vehicles to reduce emissions (Mpinga et al., 2015; Saguru et al., 2018). This makes PGMs very strategic for the automobile sector. Additionally, PGMs are essential in rechargeable batteries and superalloys (Degryse and Bentley, 2017; Sverdrup and Ragnarsdottir, 2014; Wäger et al., 2011).

The primary deposits of Nickel, Cobalt, and Platinum Group Metals are not located within the boundaries of the European Union, which implies a high dependency on imports to support its industrial development. Specifically, the EU needs approximately 700 kton of these metals annually, but only 100 kton are produced within the region (Nickel Institute, 2012). As a result, two out of the three metals analyzed in this paper, considering PGMs as a single entity, are classified in the European Commission's critical raw material list (European Commission, 2023). Although Nickel does not meet the critical raw material (CRM) thresholds, it is listed as a strategic raw material under the Critical Raw Materials Act. On the other hand, Co is deemed critical due to its crucial properties essential for high-technology industries, and PGMs are considered critical because of their strategic economic importance, low recycling rates (Graedel, 2011; Wilburn and Bleiwas, 2004), and limited availability and scarcity in the crust.

According to the International Energy Agency, the demand for Nickel is expected to double by 2040 in a conservative scenario and almost triple in the worst-case scenario (International Energy Agency, 2021). However, the maximum production peak of current Nickel reserves is expected between 2025 and 2033 (Calvo et al., 2017b; Sverdrup and Ragnarsdottir, 2014).

Cobalt is primarily produced in the Democratic Republic of Congo (DRC), which holds more than 60% of the world's production (Farjana et al., 2019). The demand for Cobalt is expected to increase by 100% by 2040 in a conservative scenario, while in the worst scenario, this value could rise to 480% (International Energy Agency, 2021). The DRC has the highest Cobalt reserves, followed by Australia, which has one-third of the DRC's reserves (Shedd, 2020). However, mining production for Cobalt in the DRC is unregulated, and there is a history of political instability and armed conflicts, making it a high-risk business environment (Shedd et al., 2017). This could affect the future of Cobalt production in this country as processors and industrial consumers become more concerned with responsible sourcing of raw materials.

The demand for PGMs is continuously increasing (Schulte, 2020), which could put the availability of these resources at risk in the

* Corresponding author.

https://doi.org/10.1016/j.mineng.2023.108150
Received 12 December 2022; Received in revised form 17 May 2023; Accepted 21 May 2023
Available online 28 May 2023

following decades. South Africa is the primary producer of Platinum, accounting for over 75% of the world's supply, with ores ranging from 7 to 10 g/t (Shaik and Petersen, 2017). Some authors have suggested that there could be enough PGM reserves for the next 200 years based on current production data and estimated reserves (Ndlovu, 2015). However, others have calculated that the maximum production peak for PGMs would occur in 2020 (Sverdrup and Ragnarsdottir, 2014). According to Valero et al. (2018) the demand for Co and PGMs could exceed their supply, creating a bottleneck.

The increasing demand for minerals are putting more and more pressure on the mining sector, which must face decreasing ore grades. As a thermodynamic fact, mining energy increases exponentially as ore grades decline (Calvo et al., 2016a). Consequently, extraction costs also increase, and mining may become unaffordable if prices remain low.

In this respect, global events directly influence commodity prices. For instance, following the onset of the war in Ukraine, the price of Ni doubled in just ten days. At present, the price of Ni remains higher than in the pre-war period. If this price increase persists over time and other metals experience similar increases, the mining industry may respond by activating lower-graded mines, which could affect total energy consumption.

Moreover, primary metal production carries massive environmental effects. As an example, up to 12 t CO2eq. per ton of ferronickel are sent to the atmosphere (Bartzas and Komnitsas, 2015). With the future demand and production expected for metals, the emissions sent to the atmosphere and the waste generated by the metal industry could be unaffordable for the future society unless some measures are taken (Spooren et al., 2020). In this respect, some studies have calculated the reduction of the environmental impact if certain metals were extracted from secondary resources. For instance, (Zhang et al., 2022) concluded that global warming associated with secondary copper extraction could be reduced sevenfold compared to primary production.

This study aims to examine the energy costs associated with extracting Ni, Co, and PGMs as ore grades in mines decrease. Previous research has explored the evolution of energy costs for gold (Palacios et al., 2019), copper (West, 2011), and lead and zinc (Magdalena et al., 2021b). For this study, a model was developed using specialized software, HSC Chemistry, which takes into account all the metallurgical processes required to refine each metal to the desired commercial grade (Outotec, 2020). The software enables thermodynamic calculations to be carried out, modeling different pyrometallurgical and hydrometallurgical flowsheets (Outotec, 2020). Moreover, cost allocation for Ni, Co, and PGMs was performed using various strategies to simulate how energy costs are associated with each metal. Lastly, several analyses were conducted to estimate the behavior of future mines during the beneficiation process and their future profitability considering metal market prices and energy costs.

2. Description of the metallurgical process

Co and Ni are typically co-mined, but Ni can be derived from two primary sources: laterites and sulfides. Approximately 70% of Ni resources are found in laterites, typically used for ferronickel production. However, the amount of Co present in laterites is typically too low to be economically feasible for extraction, so Co is usually obtained from Ni sulfides. PGMs, including Ru, Rh, Pd, Os, Ir, and Pt, can also be found in Ni ores, either dissolved or as distinct mineral grains (F. Crundwell et al., 2011; Xiao and Laplante, 2004).

Although laterite reserves are more abundant than sulfide reserves, this study will only focus on Ni sulfides, as they contain higher concentrations of Co and PGM than laterites (Piña et al., 2010). Furthermore, besides metal concentration in the ore, the specific energy required to extract Ni from laterites is also higher than the specific energy required to extract Ni from sulfide ores (Khoo et al., 2017; Mistry et al., 2016; Norgate and Jahanshahi, 2011).

After analyzing various Nickel-bearing minerals, it was decided to use pentlandite as the primary mineral ore (Alves Dias et al., 2018; Rao, 2000). Pentlandite has the highest Nickel concentration, implying lower specific energy when compared with other minerals. A standard concentration of pentlandite and other gangue minerals, such as quartz, has been established for an average mine to proceed with the simulation. Mineral composition and concentrations are also required to proceed with the simulation. Different scenarios can be created to simulate the future behavior and evolution of the mine once every mineral is set up with its concentration. Therefore, pentlandite concentration in the mine will be gradually reduced as the concentration of gangue minerals increases, simulating what could occur when the mine becomes exhausted.

Different specific energies have to be considered to carry out the simulation. For instance, ore handling involves using diesel for transportation, machines, and electricity for various units (Calvo et al., 2016a). Additionally, the increase in the concentration is achieved by increasing the g/t ratio of the metal (Nagaraj, 2005), starting from a low ratio at the beginning of the process. The purpose of the comminution process is to reduce particle size, which will increase the energy at this stage for low concentrations due to the embodied energy (Qin et al., 2022). Then, comminution is followed by a flotation process (Bulled and Mcinnes, 2005). The last stage is refining, where pure metal is obtained.

Fig. 1 represents all the main stages involved in the extraction of Ni, Co, and PGMs, highlighting the most important data introduced in the simulation. This diagram has been created following a literature review (Black et al., 2018; F. K. Crundwell et al., 2011; Metso, 2015; Napier-Munn and Barry, 2006; Rankin, 2011).

The beneficiation process is divided into three main stages: comminution, flotation, and refining. As seen, comminution and flotation stages are shared by all metals. After flotation, PGMs minerals are separated from pentlandite through gravitation (F. K. Crundwell et al., 2011). During the metallurgical stage, PGMs are refined to separate the six metals that compose PGMs (Cole and Joe Ferron, 2002; Kriek et al., 1995). Finally, pentlandite is refined to separate Ni and Co, obtaining these two metals in pure form at the end of the process.

In order to conduct the simulation, it is necessary to obtain concentration data before and after each of the main stages, including comminution, flotation, and refining. Average concentration values for each stage have been established based on various sources (Black et al., 2018; Cramer, 2007; Piña et al., 2010).

Table 1 displays the concentration of each metal at different stages of the beneficiation process. PGM is considered a single metal at this stage for simplification purposes, with a unique concentration in each step. It should be noted that the "in mined ore" figures are representative of the typical values found in literature references.

After inputting the data into the software, various scenarios were created by progressively decreasing the average concentration of each metal, as detailed in Table 2 and as supported by the consulted literature (Mills, 2022). In each scenario, the ore grade was reduced by one-third relative to the previous one, with Scenario 12 representing the lowest concentration of each metal, even falling below the crustal concentration (Valero and Valero, 2014). Currently, the lowest cut-off grade for metals is observed in gold, with a concentration of 2 g/t (2x10-4 wt-%), but technological advancements are expected to increase efficiency in the coming decades. As a result, scenarios involving values close to the crustal concentration were also investigated.

3. Simulation and results

The amount of feed at the beginning of the process significantly impacts the number and size of units required in the various processes, which in turn affects energy consumption. In order to standardize the study, a feed rate of 800 t/h has been chosen for all scenarios, which is appropriate for low-grade ores. The simulation involves considering three main energy sources, which correspond to the three stages described in the flowsheet. The first stage is comminution, where the

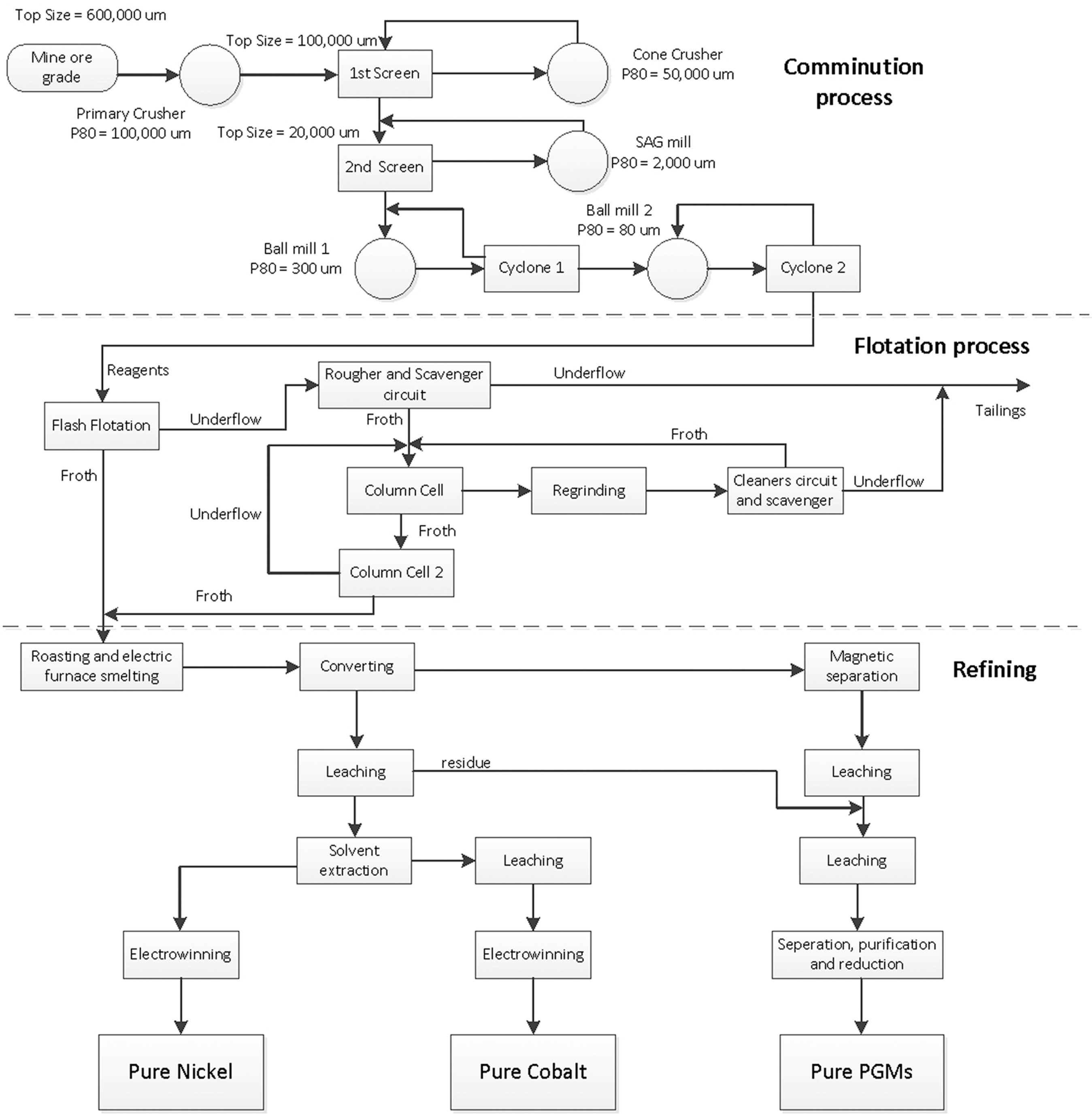

Fig. 1. Flowsheet for the extraction of Ni, Co, and PGMs.

Table 1
Concentration in different steps along the beneficiation process [data in %] (Black et al., 2018; F. K. Crundwell et al., 2011; Piña et al., 2010).

	In mined ore	After flotation	After smelting & converting
Ni	1.5–2.5	10–20	40–70
Co	0.05–0.1	0.3–0.8	0.5–2
PGMs	0.0004	0.01–0.02	0.2–0.4

size of the extracted rock is reduced to the required particle size for subsequent steps. As the ore grade decreases in each scenario, more rock must be processed to obtain the same amount of ore, resulting in an increase in embodied energy and specific energy consumption (Mudd, 2010, 2009; Norgate et al., 2010; Valero and Valero, 2012). The initial concentration at the beginning of the flotation process determines the design of the flowsheet. As the concentration decreases consecutively in the scenarios, more cleaners, column cells, roughers, and scavengers are required to achieve the desired concentration at the end of the process, increasing the specific energy of the flotation process. In contrast, the specific energy in the refining stage remains constant because the concentration at the beginning of this stage must always be the same across all scenarios.

After the simulation, the software provides data for the units used in the comminution process, including the primary crusher, cone crusher, SAG mill, ball mills, and re-grinding. Table 3 presents the specific energy consumption of each unit during the comminution process. These values

Table 2
Initial ore concentration for each scenario [data in wt-%].

	Ni	Co	PGMs		Ni	Co	PGMs
Sce. 1[A]	3	0.16	$4x10^{-4}$	Sce. 7	$4.1x10^{-3}$	$2.19x10^{-4}$	$5.49x10^{-7}$
Sce. 2	1	0.0533	$1.33x10^{-4}$	Sce. 8	$1.37x10^{-3}$	$7.32x10^{-5}$	$1.83x10^{-7}$
Sce. 3	0.33	0.0178	$4.44x10^{-5}$	Sce. 9	$4.57x10^{-4}$	$2.44x10^{-5}$	$6.1x10^{-8}$
Sce. 4	0.11	$5.93x10^{-3}$	$1.48x10^{-5}$	Sce. 10	$1.52x10^{-4}$	$8.13x10^{-6}$	$2.03x10^{-8}$
Sce. 5	0.037	$1.98x10^{-3}$	$4.94x10^{-6}$	Sce.11	$5.08x10^{-5}$	$2.71x10^{-6}$	$6.77x10^{-9}$
Sce. 6	0.012	$6.58x10^{-4}$	$1.65x10^{-6}$	Sce. 12	$1.69x10^{-5}$	$9.03x10^{-7}$	$2.26x10^{-9}$

A = concentration in mine (F. K. Crundwell et al., 2011).

Table 3
Power demand and energy required during the comminution process.

Equipment	Power demand [MW]	Specific energy [kWh/t rock]
Primary crusher	0.365	0.38
Cone crusher	0.477	0.88
SAG Mill	3.975	7.27
Ball Mill 1	22.92	12.05
Ball Mill 2	11.96	9.68
Re-grinding	3.73	10.46

will not be altered during the study as particle size reduction is required in all scenarios. The values obtained from this simulation have been compared with those reported in the literature (Latchireddi and Faria, 2013) and are within the same order of magnitude. As shown in Table 3, the highest energy consumption is from Ball Mill 1, followed by Ball Mill 2. The reduction ratio may explain this since these units aim to reduce particle size by two orders of magnitude. Interestingly, re-grinding requires less energy than SAG mills, despite having a higher specific energy. The reason for this is the particle size required for the final product. Re-grinding is introduced in the comminution process to decrease particle size considerably. Still, the efficiency drops as the process needs to be repeated more than once to achieve the desired size.

Using the Outotec Chemistry software, the energy demand for the flotation units involved in the process can be calculated, providing the total energy for the stage. Since the simulation includes multiple scenarios for the future behavior of the mine, more flotation units are required with each subsequent scenario to achieve the desired concentration. The process described in this article represents the current mining practice, but as mentioned, each following scenario will require additional roughers, cleaners, and scavengers, leading to an increase in specific energy for the entire process, as shown. Table 4 presents selected scenarios, along with the specific energy required for concentration during both the comminution and flotation stages of the beneficiation process, for comparative purposes.

The refining process is initiated once the desired concentration is achieved, and it involves various chemical processes to extract pure metals. As all the metals are initially present in the same feed, i.e., pentlandite, it needs to be sent to the metallurgical plant for further purification. Although the software can simulate the metallurgical processes, the values for the different metals are obtained from the literature for simplicity. The energy required for Ni purification is reported to be in the range of 60–100 GJ/T (Calvo et al., 2017a; Wei et al., 2020), while for Co purification, it is in the range of 72–129 GJ/T (Calvo et al., 2017a; Dai et al., 2018). In the case of PGMs, the value chosen for energy consumption during the refining stage is in the range of 315–566 GJ/T (F. Crundwell et al., 2011; Kingsbury and Thathiana Benavides, 2021).

Table 4
Specific energy for concentration in the comminution and flotation stages [data in GJ/t-ore].

GJ/t-rock	Comminution	Flotation	Both
Scenario 1 (conc. in mine)	5,526.37	2.29	5,528.66
Scenario 4	149,212	3,800.6	153,012.6
Scenario 8	$1.21\ x10^{7}$	54,559.3	$1.21\ x10^{7}$
Scenario 12	$9.79\ x10^{8}$	3,098,853	$9.82\ x10^{8}$

Note that PGMs are composed of six different metals.

4. Analysis and discussion

4.1. Energy share in the different stages of the beneficiation process

As mentioned earlier, the decreasing ore grade of certain minerals in mines may result in a capacity shortage to meet market demand (Calvo et al., 2016b; Northey et al., 2014). While it is impossible to predict the future of resource availability in each mine, it is possible to estimate the behavior of specific energy for concentration for each extracted metal. It should be noted that for the sake of simplicity, all six PGMs have been considered as a single metal in this analysis. Although the beneficiation process is the same for all metals, they are ultimately separated during refining. If the analysis had been performed for each PGM individually, it would not have affected the study's final outcome.

When the concentration of a metal is very low, ore handling becomes a critical process. The lower the ore grade, the more rock needs to be treated, processed, and transported, which in turn increases the amount of diesel required to transport the rock from the mine to the processing plant. For the three metals analyzed in this study, we consulted the Ecoinvent database for ore handling data (Ecoinvent, 2007). While the energy required for PGMs represents the lowest share of total energy, ore handling can still account for a significant portion of the energy consumption in the beneficiation process. It can vary widely depending on the metal being extracted. For example, in this study, the ore handling value for PGMs is 1,030 GJ/t-PGMs, while for Ni it is only 11.2 GJ/t-Ni. In the case of Co, it represents almost 40% of the total energy required for the rest of the stages. These differences can be attributed to the ore grade at the beginning of the process.

4.2. Cost allocation

Most mines are designed to extract more than one metal to maximize mine exploitation. During the extraction process until the end of the metallurgy process, there are common stages for all the metals extracted, which are needed to allocate different costs. Allocation is key when energy costs are being calculated since different results can be obtained depending on the type of allocation selected. Accordingly, different cost allocations have been reviewed to select the most accurate for this study. Hence, this analysis will focus on selecting Bond Index values and comparing different cost allocation systems, using: 1) metal market prices, 2) data from the Ecoinvent database, and 3) a thermodynamic allocation procedure explained below.

When the ore grade is very low, the comminution stage has the highest share of energy consumption. Therefore, Bond index is essential for calculating the energy at this stage since the energy calculated could be several times higher or lower depending on the value chosen, as demonstrated in previous studies (Magdalena et al., 2022; Palacios et al., 2019). Therefore, selecting an accurate Bond index that reflects the reality of the ore being treated is crucial. A wide range of Bond index values can be applied, from 2 kWh/t to 24 kWh/t, depending on the mineralogy of the rock in the mine. This study has chosen an average value of 13.65 kWh/t since it is a typical value for ores containing Ni (Michaud, 2015).

Efficiency factors are also considered in the data calculation, not just the Bond index. This is because the efficiency of the mills is never 100%, and it can increase the specific energy required by up to 10–20% for regular particle sizes (Rowland, 1999), applying an efficiency ranging from 90 to 95% as average in this study. Moreover, if the particle size required is extremely small, the efficiency decreases even further, requiring more energy to achieve the same result.

Regarding cost allocation, the first procedure (Fig. 2A) is based on the average metal prices between 2010 and 2020, as well as the production, as shown in Equation (1).

$$Allocation = \frac{P_i x M_i}{\Sigma_{i=1}^{n}(P_i x M_i)} \quad (1)$$

Where P_i is the market price, and M_i is mine extraction. This allocation is calculated by multiplying the annual production of each metal by the mentioned average price. The resulting values are then divided by the sum of the three metals, obtaining the share of each metal in the total revenue. These percentages can vary depending on the year chosen since metal prices can be very volatile. Using this approach, the cost allocation obtained for Ni, Co, and PGMs are 61%, 6%, and 33%, respectively.

The second option for cost allocation involves obtaining values from the Ecoinvent database (Ecoinvent, 2007), and the results are shown in Fig. 2B. This database provides allocation values for two different mines located in South Africa and Russia. The cost allocation is different in both mines as it is calculated based on the main metal sold. Therefore, allocation can vary depending on the metal sold and the by-products extracted. In the South African mine, the cost allocation for Ni represents 7%, while in the Russian mine, it represents 47%. The average of both mines has been calculated based on their respective allocation by mass and revenue, resulting in 50% for Ni, 30% for Co, and 20% for PGMs.

The proposed cost allocation based on Thermodynamic Rarity values of the metals (Valero and Valero, 2015) is shown in Fig. 2C. Thermodynamic Rarity is an index that assigns an average energy value to each metal based on its global scarcity, embodied energy, and energy replacement cost (ERC) according to the Second Law of Thermodynamics. The embodied energy of a metal refers to the total energy required to extract it from the mine to its use in the industry. On the other hand, ERC is the energy required to restore a mineral from a dispersed state to its initial concentration (Valero et al., 2013). Thermodynamic rarity values can be consulted in (Valero et al., 2021). The rationale behind this approach is that metals with a higher Thermodynamic Rarity require more energy to be produced, and therefore, their costs should reflect their scarcity. The annual production is multiplied by the Thermodynamic Rarity value for each metal to obtain the cost distribution, which is 40% for Ni, 29% for Co, and 31% for PGMs.

Table 5 summarizes the values obtained with each methodology used for cost allocation calculation. In the first case, the distribution provides a larger share to those metals with higher prices, although the amount of metals extracted may be lower. This allocation is not based on physical properties or sustainability conditions and can be very volatile, depending on political and demand factors. In the second case, using data obtained from Ecoinvent, the allocation in tons could differ depending on the mine and the primary metal extracted. These two approaches, however, do not adequately reflect the situation of these metals and their scarcity. The third approach, based on Thermodynamic Rarity, provides that cost allocation is not based on economic terms but rather on the scarcity of the planet's crust. More in-depth and complementary studies have analyzed different cost allocation strategies considering the market price, tonnage, and energy (Valero et al., 2015).

As shown in Fig. 2, cost allocation based on Thermodynamic Rarity and Ecoinvent can provide similar results. However, for the purpose of this paper and the analysis carried out, Thermodynamic Rarity has been selected as it places greater emphasis on metal scarcity, which is a physical indicator.

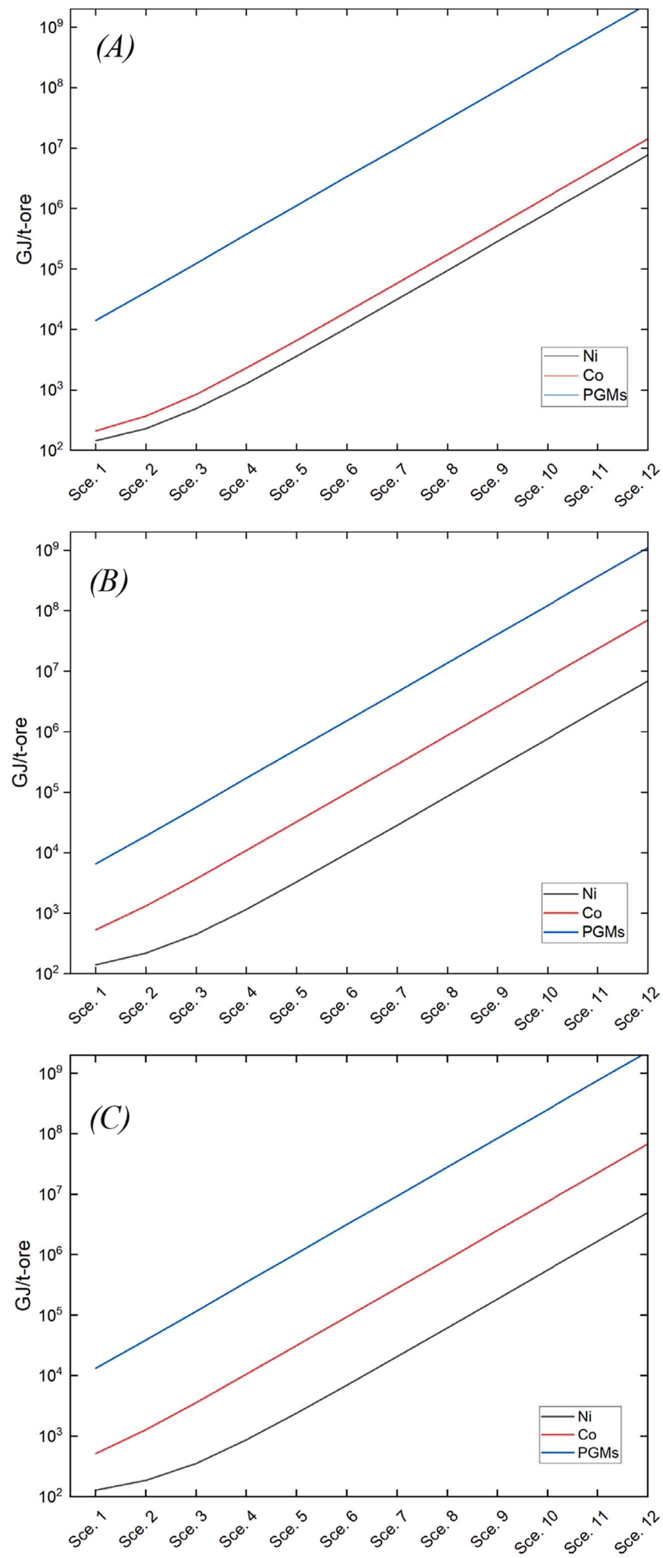

Fig. 2. Cost allocation for Ni, Co and PGM using different approaches. A) metal market prices, B) Ecoinvent database, C) Thermodynamic Rarity. Specific energy for concentration is in GJ/t-ore.

4.3. Limit of recovery

Different organizations and authors have made various estimates for

Table 5
Summary of the different types of cost allocations analyzed.

	Ni	Co	PGMs
Market price (2010–2020)	61%	6%	33%
Ecoinvent	50%	30%	20%
Thermodynamic Rarity	40%	29%	31%

the amount of Nickel resources. For example, the British Geological Survey (2008) estimated Nickel resources at 262 million tonnes (MT), while the Nickel Institute (2016) estimated it at 300 MT. However, not all of these resources are economically viable to extract due to technological constraints and other factors. Studies have been carried out to determine the grade limit for extracting minerals (Norgate et al., 2010; Rötzer and Schmidt, 2018; West, 2011). Some authors suggest that future mines will not be restricted by depletion but by dilution, as advances in technology may make it viable to extract elements that were previously not feasible (West, 2011). Others argue that the issue will be related to the price, as dealing with lower ore grade mines would require more energy for extraction, increasing prices and making these mines profitable (Rötzer and Schmidt, 2018).

In this paper, we have used the version proposed by Rötzer and Schmidt (2018) for analyzing the specific energy for the concentration of depleted mines, as it is not possible to predict how technology will evolve in the following years. Therefore, the best available technology has been applied to develop this model (Lenzen, 2008). In terms of ore grade, some authors (Sverdrup and Ragnarsdottir, 2014) mention that the limit of extraction for a mineral in any mine is 0.5 g/t, as there is currently no technology to lower concentrations, and it would not be economically viable.

We propose a new ore grade limit, the Limit of Recovery (LOR) to analyze the specific energy for concentration of depleted mines. We propose to use the energy needed to extract a ton of PGM from tailings as a baseline for setting the LOR. In this case, the concentration of PGMs in tailings comes from literature, which is set up at 2.4 $\times$ 10^{-6} wt-% (F. Crundwell et al., 2011). This concentration corresponds to an energy cost of 992,124 GJ/t-PGMs, as extracted from Fig. 3C. Therefore, it is possible to calculate which ore grade corresponds to 992,124 GJ for Ni and Co and set their corresponding LOR values.

Interestingly, the ore grade for Nickel that could be reached by applying the mentioned energy limit would be below crustal concentration, which makes little sense. This is why the chosen LOR for Nickel is assumed to be the average crustal concentration. Table 6 shows the final LOR values used in this study for the three analyzed commodities.

Fig. 3 depicts the expected trend for the beneficiation process obtained for Ni, Co, and PGMs after carrying out the simulation. Each black dot in the figure represents a scenario, and not all 12 scenarios are present in all the figures due to scale reasons. In this case, the cost allocation has been carried out using Thermodynamic Rarity. In addition to the dots representing the ore grade for each scenario, three other key points should be considered. Firstly, the current ore grade values have been obtained from the literature (F. K. Crundwell et al., 2011). Secondly, various studies have demonstrated that recovering metals from tailings can be profitable (Alfonso et al., 2020; Morin and D'Hugues, 2007) and could be critical to meet future metal demands, especially since the concentration in those tailings could be similar to the current ore grades in mines (Magdalena et al., 2021a). The concentration for PGM in tailings is 2.4x10^{-6} wt-%, 0.3% for Ni, and 0.014% for Co (F. K. Crundwell et al., 2011). The last key point is the LOR, which corresponds to the first column in Table 6. In the case of Ni, the LOR value is equivalent to the crustal concentration, as mentioned previously.

In the case of Ni, the primary energy share corresponds to the refining process in the first scenario (Fig. 3A). However, as the ore grade decreases, comminution becomes more relevant, which can be observed in the curve shifting towards an exponential trend. The metal content in

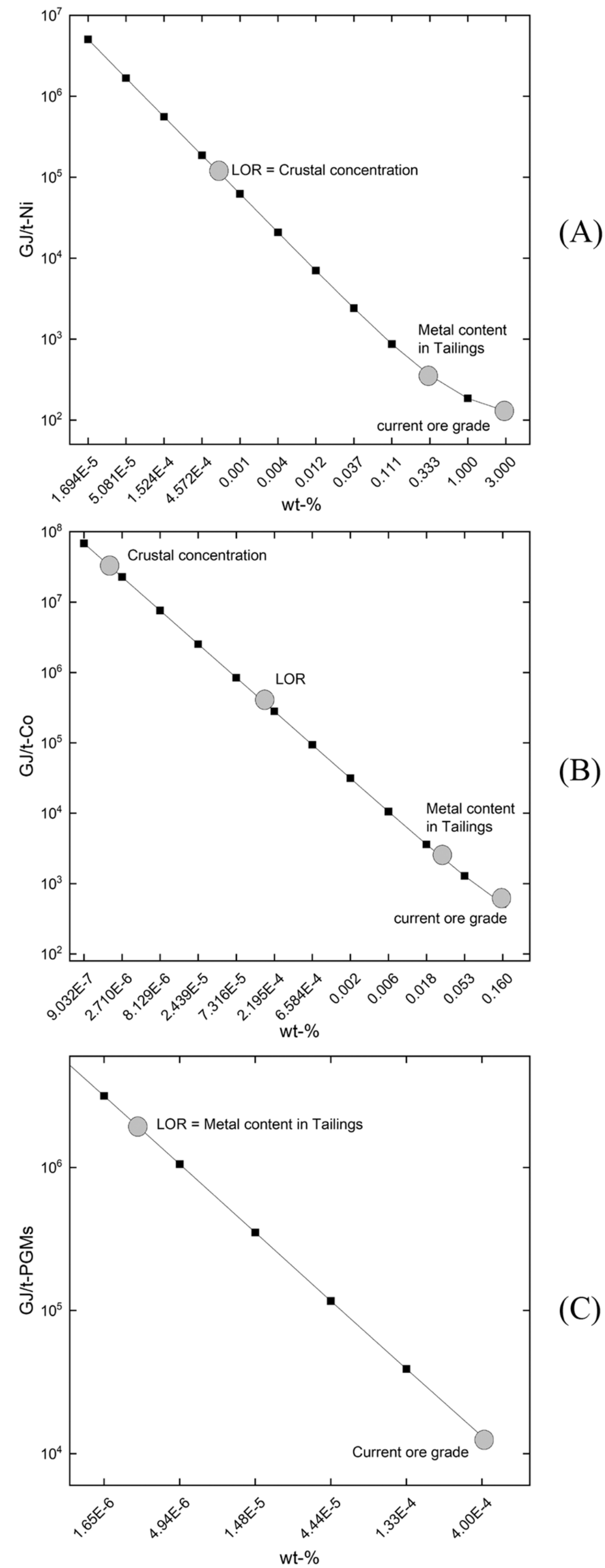

Fig. 3. Estimation of the specific energy for concentration for Ni (A), Co (B), and PGMs (C) [GJ/t-ore] with cost allocation carried out using Thermodynamic Rarity.

Table 6
Limit of recovery (LOR) as proposed in this study and average crustal ore grade [wt-%].

Metal	LOR	Crustal concentration (Valero et al., 2011)
Nickel	4.00 x10^{-4}	4.00x10^{-4}
Cobalt	6.89 x10^{-5}	5.15 x10^{-7}
PGMs	2.40 x10^{-6}	3.95 x10^{-8}

tailings (0.3 wt-%) is reached around Scenario 3, which could be very relevant in the near future as current tailings still contain a significant amount of Ni that could soon become economically viable to recover if the average ore grade in the mines decreases to that extent. A similar situation can be seen for Co (Fig. 3B), where the metal content in tailings is reached before Scenario 3. However, the metal content in tailings for Co is one order of magnitude lower than that for Ni. In both cases, the LOR is still several orders of magnitude lower, and as stated before, in the case of Ni, the LOR value is equivalent to the crustal concentration. As for PGMs (Fig. 3C), the current ore grade in the mines is considerably lower. As explained, since the limit for LOR was established using the energy needed to extract a ton of PGM from tailings, in this case, LOR is equivalent to the ore grade in tailings. Comparing these values, it can be seen that LOR is only two orders of magnitude lower than the current ore grade. This situation could create potential supply problems in the future if all mines start becoming depleted.

4.4. Analysis and implications of energy consumption

An estimation was made to observe how the specific energy for concentration (in GJ/t of metal) changes as the ore grade decreases until it is almost 0 wt-%. Three values have been used for comparative purposes: current ore grade in mines, metal content in tailings, and LOR (minimum concentration). To put these results into perspective, they have been converted into tons of oil equivalent (TOE) per ton of metal. Table 7 summarizes the values obtained for each scenario and metal.

In 2020, the global production of Ni was 2,510,000 tons, 142,000 tons for Co, and 383 tons for PGMs (U.S. Geological Survey, 2022), equivalent to an energy consumption of 9.56 MTOE (scenario A). This represents over 31% of the total Australian mining energy consumption in 2019 (Australian Government, 2020). If, for instance, all PGM reserves were to be extracted, which according to the U.S. Geological Survey (2022) are estimated at 70 kT, more than 22 MTOE of energy would be needed, representing 16% of the total energy consumption in Australia in 2019 (Australian Government, 2020).

Energy consumption dramatically increases when the metal content reduces until the tailings concentration (scenario B). For Ni, energy consumption increases almost three-fold, while for Co, this value increases seven-fold when compared to scenario A (current ore grade). A more drastic increase can be seen when comparing scenarios B and C.

4.5. Economic assessment

The simulation and the specific energy data obtained can now be used to conduct an economic evaluation to assess the energy costs for each metal and compare them to their current market prices. Comminution and flotation primarily rely on electricity, while diesel is used during the ore handling phase, and natural gas and coal are used during different metallurgical processes. Therefore, since all previously obtained values are in energy terms, converting them into monetary terms using energy prices is straightforward. The electricity market is very volatile and depends on many factors. Therefore, electricity prices are very variable, directly affecting the energy cost to mine and refine metals and, ultimately, the final price of metals.

Australia has a significant mining industry and one of the world's largest mineral reserves, so its electricity and energy prices are used in this study. The Australian Government publishes more reliable electricity and energy prices than other main-supplying countries. According to the Australian Energy Regulator, the average prices for electricity, natural gas, and coal in 2020 were 0.29 USD/kWh, 0.073 USD/kWh, and 62 USD/ton, respectively, while the diesel price was 1.22 USD/l (Australian Government, 2021). Combining this information with the specific energy previously calculated, we can obtain the energy costs for the simulations for each metal as a function of the ore grade's evolution (Fig. 4).

Additionally, an economic assessment can be carried out by comparing the energy costs of each metal in each scenario and simulation with their current market prices. According to USGS statistics, the average Ni price was 10,403 USD/ton in 2022, while for Co it was 55,731 USD/ton, and more than 29,580,000 USD/ton for PGMs (U.S. Geological Survey, 2022). The PGMs price was calculated as an average of the six metals included in the PGMs group. Since metal market prices can be volatile and change considerably over time, the analysis in Fig. 4 includes three prices: 1) 2022 price, 2) maximum historical price, and 3) current price multiplied by ten. Using the energy costs calculated for scenario 1, the share of the metal price that corresponds to the energy costs can be obtained. For Ni, the current energy costs represent 63% of the metal price, while for Co, this number is 67%. In contrast, for PGMs, the energy costs only represent around 3% of the metal price. Electricity and diesel prices are subject to fluctuations due to economic and political issues. For example, in Australia, the electricity price increased by 100% at the beginning of 2022 (Australian Government, 2021). Therefore, different scenarios have been created considering: 1) the aforementioned energy prices, 2) a two-fold increase in energy prices, and 3) a five-fold increase in energy prices.

Analyzing the relationship between energy and metal market prices, the case of Ni is particularly representative because the striped area covers situations where extraction from tailings could become profitable given the current energy price and even if this price were to double. A different situation can be seen if the energy price increases fivefold. In this case, extracting Ni from tailings would not be economically beneficial, even with a severe increase in the metal market price. Regarding Co, the striped area would cover the first two energy price scenarios (current price and price multiplied by a factor of two) when considering the current ore grade in mines. Still, in the case of tailings, the situation is different and could only be profitable under certain conditions while maintaining current energy prices. Even a slight increase in energy price could make this process unaffordable. if the metal market price remains within the striped area. However, if the Co price increases, it would be viable to recover the metal from tailings and even from materials with an even lower concentration. All the numbers are listed in Table 8.

The energy costs associated with tailings processing would be significantly higher for PGMs as it would be necessary to process a larger amount of rock. However, due to the scarcity and high market prices of PGMs, the current energy cost represents only 3% of the metal price.

Table 7
Comparison of the specific energy for each metal for three scenarios: A) current ore grade, B) metal content in tailings, C) LOR.

	Ni			Co			PGM		
Sce.	wt-%	GJ/t-Ni	TOE/t-Ni	wt-%	GJ/t-Co	TOE/t-Co	wt-%	GJ/t-PGMs	TOE/t-PGMs
A	3	128.39	3.06	0.16	514.86	12.29	4x10^{-4}	13,210.65	315.53
B	0.3	355.49	8.49	0.01	3,601.84	86.02	2.4x10^{-6}	992,124	23,696
C	4x10^{-4}	992,124	23,696	6.9x10^{-5}	992,124	23,696	2.4x10^{-6}	992,124	23,696

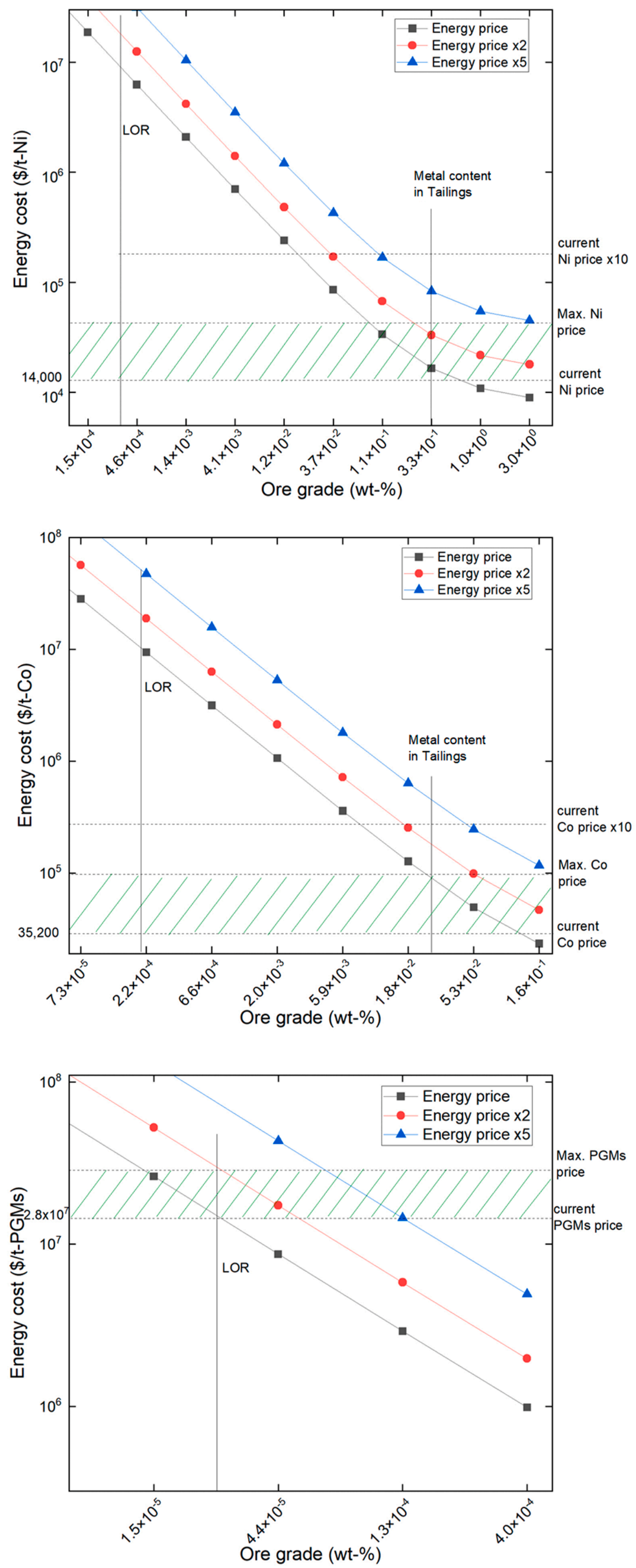

Fig. 4. Energy cost as a function of the ore grade for Ni, Co and PGMs. The striped area represents the area between each metal's current and maximum historical price.

Table 8
Energy cost with different ore grades and different energy prices [$/t-ore].

	wt-%	Current	x2	x5	Commodity price[1]
Ni	3	9,340	18,680	46,700	10,403 $/ton
	0.3	114,429	2.39E + 04	5.98E + 04	
	$4x10^{-4}$	25,754,851	3.96E + 04	9.90E + 04	
Co	0.16	23,738	47,476	118,690	55,731 $/ton
	0.016	130,746	261,492	653,730	
	$6.9x10^{-5}$	29,291,647	58,583,294	146,458,235	
PGMs	$4x10^{-4}$	489,170	978,340	2,445,850	29,580,000 $/ton
	$2.4x10^{-6}$	113,996,791	227,993,582	569,983,955	

[1] (U.S. Geological Survey, 2022).

Consequently, the striped area representing profitable scenarios for tailings processing is much larger with respect to the current ore grade compared to the other two elements analyzed. The high price of PGMs can only be compared to that of gold, which explains why the profitability threshold is so low. In this study, the metal content of PGMs in tailings was used to determine the minimum energy required to extract any metal. If the ore grade decreases until that point and energy costs remain constant, it would still be possible to recover PGMs. A two-fold increase in energy costs would be required to make the recovery unviable. However, other costs such as operation, maintenance, and management must also be factored in, and energy costs from other metals could reduce the initial share, making the process more feasible.

Finally, PGMs present a unique situation due to their scarcity in the crust and their high market prices. As previously mentioned, the current energy cost represents only 3% of the current PGMs price. This explains why the striped area is so high with respect to the current ore grade, compared to the two previous elements. The high price of PGMs, which can only be compared to that of gold, justifies this situation. In this case, the PGMs metal content in tailings has been chosen as the LOR to obtain the minimum energy needed to extract any metal. Even if the ore grade decreases to that point, it would still be possible to recover PGMs if the energy costs are maintained. The energy costs would have to increase by more than two-fold to make the recovery unprofitable. However, the price could hold some energy costs coming from the other metals, reducing the initial share, obtaining more benefits. Other costs apart from energy must be added to these prices, such as operation, maintenance, and management.

It is important to note that mines are designed to be economically feasible, which means that cost allocations are crucial to maximize metal extraction. As a result, it is common for the metal that generates the maximum profit to receive a higher cost allocation since its market price is higher (Magdalena et al., 2022). Conversely, companion metals with a lower market price receive less allocation to obtain more benefits when metals are sold. Although there are no common criteria for cost allocation, economic assessment is widely used since mining companies need to make a profit from extracting minerals. Therefore, an analysis was conducted to determine what would happen if allocation changed. Since Ni is the most extracted metal out of the three studied in this paper, a larger share of the total cost allocation was considered, ranging from 40% to 70%. Table 9 summarized the results of this analysis. In this example, different allocations have been provided for the three metals studied, obtaining different costs depending on the allocation procedure used.

Based on the results of this analysis, the main conclusion is that by increasing the cost allocation for Ni, the costs for Co and PGMs reduce considerably (almost 50% in the case of PGMs), while Ni prices increase only slightly. This can be easily seen if the energy costs are compared with current metal prices. As mentioned, the energy cost for Ni, Co, and

Table 9
Energy costs calculated according to different cost allocation procedures and energy prices [$].

	Current energy price			Current energy price x2			Current energy price x5		
	Ni	Co	PGMs	Ni	Co	PGMs	Ni	Co	PGMs
Ni 40% Co 29% PGMs 31%	8,985	23,292	983,960	17,970	46,583	1,967,920	44,925	116,459	4,919,799
Ni 50% Co 24% PGMs 26%	9,223	21,063	829,338	18,446	42,125	1,658,676	46,115	105,313	4,146,690
Ni 60% Co 19% PGMs 21%	9,461	18,833	674,716	18,922	37,667	1,349,432	47,305	94,167	3,373,580
Ni 70% Co 14% PGMs 16%	9,699	16,604	520,094	19,398	33,208	1,040,188	48,495	83,021	2,600,470

PGMs represents 63%, 67%, and 3%, respectively, of the current price. However, if this comparison were made with the highest allocation for Ni (70%), the energy cost associated with this metal would be 69% of the current Ni price, while for Co, it would change to 47% and 1.5% for PGMs. Mining companies can use these different allocations to determine the price of the metals they are extracting, as it can lead to significant differences in some metals.

5. Conclusions

Metals have become increasingly critical due to their expanding usage in technological devices and industries, and this demand is expected to persist in the future. This study scrutinized Nickel, Cobalt, and Platinum Group Metals from diverse viewpoints, taking into account key factors such as the energy cost of extraction, the limit of recovery (LOR) for each commodity, and the impact of price variation in the mining sector. These approaches allowed for the evaluation of outcomes in various scenarios.

HSC Chemistry software was employed to simulate the energy consumption behavior in a mine as the ore grade declines. For this purpose, the specific energy for concentration was calculated for various processes carried out during the beneficiation process, including comminution, flotation, and refining stages. The amount of energy required to extract a ton of different metals was determined by considering current concentrations in mines, in tailings, or when an ore grade limit (LOR), as specified in this paper, is reached. Energy costs would increase more than 250% for Ni, 700% for Co, and 7,500% for PGMs if they were extracted from tailings. In these cases, for extraction to be viable, the market price of Ni should at least double, and that of Co and PGMs should be more than two and three times higher, respectively.

The economic evaluation also underscored the importance of cost allocation. Currently, the energy cost represents 63%, 67%, and 3% of the price of Ni, Co, and PGMs, respectively. However, if the cost allocation changes, it may be feasible to extract a specific metal, despite a reduction in the ore grade.

As demonstrated in this paper, the cost to extract and refine these commodities will become unaffordable as the ore grades approach the limit of recovery. Environmental impacts will also tremendously grow, putting ecosystems at risk.

Therefore, it is crucial to work on postponing the depletion of mines as much as possible. Recycling could be an excellent solution in this regard. However, the recycling rates for some of the metals analyzed in this study, including many others critical for the green economy, are considerably low. Even if millions of devices containing those metals are manufactured daily, their dispersive use makes it challenging to recover them. Currently, it is still more profitable to resort to primary extraction than to try to recover these small quantities, but this may not always be the case in the future.

CRediT authorship contribution statement

Ricardo Magdalena: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Alicia Valero:** Supervision, Validation, Writing – review & editing. **Guiomar Calvo Superivision:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This research was funded by the Spanish Ministry of Economy and Competitiveness (PID2020-116851RB-I00).

References

Alfonso, P., Hamid, S.A., Anticoi, H., Garcia-Valles, M., Oliva, J., Tomasa, O., López-Moro, F.J., Bascompta, M., Llorens, T., Castro, D., Polonio, F.G., 2020. Liberation characteristics of ta–sn ores from penouta, nw spain. Minerals 10, 1–22. https://doi.org/10.3390/min10060509.
Alves Dias, P., Blagoeva, D., Pavel, C., Arvanitidis, N., 2018. Cobalt: demand-supply balances in the transition to electric mobility. Publications Office of the European Union. https://doi.org/10.2760/97710.
Australian Government, 2020. Australian Energy Update 2020. Aust, Energy Stat, p. 46.
Australian Government, 2021. Wholesale statistics [WWW Document]. Aust, Energy Regul https://www.aer.gov.au/ (accessed 9.22.22.
Bao, Y., Shao, L., Xing, G., Qi, C., 2019. Cobalt, nickel and iron embedded chitosan microparticles as efficient and reusable catalysts for Heck cross-coupling reactions. Int. J. Biol. Macromol. 130, 203–212. https://doi.org/10.1016/j.ijbiomac.2019.02.143.
Bartzas, G., Komnitsas, K., 2015. Life cycle assessment of ferronickel production in Greece. Resour. Conserv. Recycl. 105, 113–122. https://doi.org/10.1016/j.resconrec.2015.10.016.
Black, Z.J., Brown, J.J., Dempers, N., Drielick, T.L., Ibrado, A.S., Patterson, E.L., Thomas, R.J., Ubl, J.S., Welhener, H.E., 2018. NorthMet Project, Technical report.
British Geological Survey, 2008. Definition, mineralogy and deposits.
Bulled, D., Mcinnes, C., 2005. Flotation plant design and production planning through geometallurgical modelling. Australas. Inst. Min. Metall. Publ. Ser. 3, 8.
Calvo, G., Mudd, G., Valero, A., Valero, A., 2016a. Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? Resources 5, 36. https://doi.org/10.3390/resources5040036.
Calvo, G., Valero, A., Valero, A., 2016b. Material flow analysis for Europe: An exergoecological approach. Ecol. Indic. 60, 603–610. https://doi.org/10.1016/j.ecolind.2015.08.005.
Calvo, G., Valero, A., Valero, A., 2017a. Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe. J. Ind. Ecol. 22, 839–852. https://doi.org/10.1111/jiec.12624.
Calvo, G., Valero, A., Valero, A., 2017b. Assessing maximum production peak and resource availability of non-fuel mineral resources: Analyzing the influence of

extractable global resources. Resour. Conserv. Recycl. 125, 208–217. https://doi.org/10.1016/j.resconrec.2017.06.009.
Cárdenas-Triviño, G., Elgueta, C., Vergara, L., Ojeda, J., Valenzuela, A., Cruzat, C., 2017. Chitosan doped with nanoparticles of copper, nickel and cobalt. Int. J. Biol. Macromol. 104, 498–507. https://doi.org/10.1016/j.ijbiomac.2017.06.040.
Cole, S., Joe Ferron, C., 2002. Review of the Beneficiation and Extractive Metallurgy of the Platinum Group Elements, Highlighting Recent Process Innovations. SGS Miner. Serv. 1, 1–43.
Commission, E., 2023. Study on the Critical Raw Materials for the EU. https://doi.org/10.2873/725585.
Cramer, L.A., 2007. The Extractive Metallurgy of South Africa ' s Platinum Ores updated, 1–15.
Crundwell, F., Moats, M., Ramachandran, V., Robinson, T., Davenport, W., 2011a. Smelting of Nickel Sulfide Concentrates by Roasting and Electric Furnace Smelting, in. In Book: Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals. 199–214. https://doi.org/10.1016/B978-0-08-096809-4.10017-6.
Crundwell, F.K., Moats, M.S., Robinson, T.G., Ramachandran, V., Davenport, W.G., 2011b. Extractive Metallurgy of Nickel. Cobalt and Platinum-Group Metals, Elsevier Ltd.
Dai, Q., Kelly, J.C., Elgowainy, A., 2018. Cobalt Life Cycle Analysis Update for the GREET Model.
Degryse, P., Bentley, R.A., 2017. Archeological Geochemistry: A Comprehensive Reference Source on the Chemistry of the Earth. Encycl. Geochemistry 1–11. https://doi.org/10.1007/978-3-319-39193-9.
Ecoinvent, 2007. Life Cycle Inventories of Metals.
Farjana, S.H., Huda, N., Mahmud, M.A.P., 2019. Life cycle assessment of cobalt extraction process. J. Sustain. Min. 18, 150–161. https://doi.org/10.1016/j.jsm.2019.03.002.
Fernandes, A., Afonso, J.C., Dutra, A.J.B., 2013. Separation of nickel(II), cobalt(II) and lanthanides from spent Ni-MH batteries by hydrochloric acid leaching, solvent extraction and precipitation. Hydrometallurgy 133, 37–43. https://doi.org/10.1016/j.hydromet.2012.11.017.
U.S. Geological Survey, 2022. Mineral Commodity Summaries 2022.
Graedel, T.E., 2011. Recycling Rates of Metals. A status Report.
Nickel Institute, 2012. Nickel in the European Union.
Nickel Institute, 2016. The life of Ni.
International Energy Agency, 2021. Total cobalt demand by sector and scenario, 2020–2040 [WWW Document]. Role Crit. Miner. Clean Energy Transitions.
Khoo, J.Z., Haque, N., Woodbridge, G., McDonald, R., Bhattacharya, S., 2017. A life cycle assessment of a new laterite processing technology. J. Clean. Prod. 142, 1765–1777. https://doi.org/10.1016/j.jclepro.2016.11.111.
Kingsbury, K., Thathiana Benavides, P., 2021. Update of Platinum Production and Addition of Platinum-Group Metals (PGMs) to GREET.
Kriek, R., j., Engelbrecht, W. j., Cruywagen, J.J.,, 1995. Separation and recovery of some platinum group metals (PGMs) by means of selective photocatalytic reduction. J. South African 75–82.
Latchireddi, S., Faria, E., 2013. Achievement of high energy efficiency in grinding mills at Santa Rita, 45th Annual Meeting of the Canadian Mineral Processors. Ottawa.
Lenzen, M., 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Convers. Manag. 49, 2178–2199. https://doi.org/10.1016/j.enconman.2008.01.033.
Magdalena, R., Valero, A., Calvo, G., Alguacil, F.J., Lopez, F.A., 2021a. Simulation to Recover Niobium and Tantalum from the Tin Slags of the Old Penouta Mine: A Case Study. Minerals 11, 1–12. https://doi.org/10.3390/min11101123.
Magdalena, R., Valero, A., Valero, A., Palacios, J., 2021b. Mining energy consumption as a function of ore grade decline: the case of lead and zinc. J. Sustain. Min. 20, 109–121.
Magdalena, R., Calvo, G., Valero, A., 2022. The Energy Cost of Extracting Critical Raw Materials from Tailings: The Case of Coltan. Geosci. 12, 1–15.
Magistretti, S., Dell'Era, C., Verganti, R., 2020. Searching for the right application: A technology development review and research agenda. Technol. Forecast. Soc. Change 151, 119879. https://doi.org/10.1016/j.techfore.2019.119879.
Metso,, 2015. Basics in minerals processing, 10th ed. Metso Corporation.
Michaud, D., 2015. Table of Bond Work Index by Minerals [WWW Document]. 911 Metall. URL https://www.911metallurgist.com/blog/table-of-bond-work-index-by-minerals (accessed 5.16.22).
Mills, R., 2022. Copper: the most important metal we're running short of [WWW Document]. Ahead herd. https://aheadoftheherd.com/.
Mistry, M., Gediga, J., Boonzaier, S., 2016. Life cycle assessment of nickel products. Int. J. Life Cycle Assess. 21, 1559–1572. https://doi.org/10.1007/s11367-016-1085-x.
Morin, D.H.R., D'Hugues, P., 2007. Bioleaching of a cobalt-containing pyrite in stirred reactors: A case study from laboratory scale to industrial application. Biomining. 35–55. https://doi.org/10.1007/978-3-540-34911-2_2.
Mpinga, C.N., Eksteen, J.J., Aldrich, C., Dyer, L., 2015. Direct leach approaches to Platinum Group Metal (PGM) ores and concentrates: A review. Miner. Eng. 78, 93–113. https://doi.org/10.1016/j.mineng.2015.04.015.
Mudd, G.M., 2009. The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future. Monash University and Mineral Policy Institute, Department of Civil Engineering.
Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resour. Policy 35, 98–115. https://doi.org/10.1016/j.resourpol.2009.12.001.
Nagaraj, D.R., 2005. Minerals Recovery and Processing. Kirk-Othmer Encyclopedia of Chemical Technology. https://doi.org/10.1002/0471238961.1309140514010701.a01.pub2.
Napier-Munn, T., Barry A., W., 2006. Mineral Processing Technology. An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery, 7th ed, Wills' Mineral Processing Technology. B&H publisher. https://doi.org/10.1016/b978-075064450-1/50000-x.
Ndlovu, J., 2015. Precious Metals Supply. ANGLO Am. Platin. 1–21.
Norgate, T., Jahanshahi, S., 2011. Assessing the energy and greenhouse gas footprints of nickel laterite processing. Miner. Eng. 24, 698–707. https://doi.org/10.1016/j.mineng.2010.10.002.
Norgate, T., Haque, N., Wright, S., Jahanshahi, S., 2010. Opportunities and technologies to reduce the energy and water impacts of deteriorating ore reserves. Sustain. Min. Conf. 1, 128–137.
Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resour. Conserv. Recycl. 83, 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005.
Orefice, M., Audoor, H., Li, Z., Binnemans, K., 2019. Solvometallurgical route for the recovery of Sm Co, Cu and Fe from SmCo permanent magnets. Sep. Purif. Technol. 219, 281–289. https://doi.org/10.1016/j.seppur.2019.03.029.
Outotec,, 2020. OUTOTEC HSC CHEMISTRY SOFTWARE [WWW Document]. accessed 12.4.19. https://www.outotec.com/.
Palacios, J.L., Abadias, A., Valero, A., Valero, A., Reuter, M.A., 2019. Producing metals from common rocks: The case of gold. Resour. Conserv. Recycl. 148, 23–35. https://doi.org/10.1016/j.resconrec.2019.04.026.
Parasuraman, A., 2000. Technology Readiness Index (Tri): A Multiple-Item Scale to Measure Readiness to Embrace New Technologies. J. Serv. Res. 2, 307–320. https://doi.org/10.1177/109467050024001.
Piña, R., Gervilla, F., Barnes, S.-J., Ortega, L., Martinez-Frias, J., Lunar, R., 2010. Platinum-Group Element Concentrations in Pyrrhotite , Pentlandite , Chalcopyrite and Pyrite from the Aguablanca Ni- Cu Ore Deposit (Southwest Spain). 11th Int. Platin. Symp. June, 4.
Qin, Y., Han, Y., Gao, P., Li, Y., Yuan, S., 2022. Characterization of chalcopyrite ore under high voltage pulse discharge: Particle size distribution, fractal dimension, specific energy consumption, grinding kinetics. Miner. Eng. 184, 107631 https://doi.org/10.1016/j.mineng.2022.107631.
Rankin, W., 2011. Minerals, Metals and Sustainability. Meeting Future Material Needs, CSIRO publishing. https://doi.org/10.1071/9780643097278.
Rao, G.V., 2000. Nickel and Cobalt Ores: Flotation. Encycl. Sep. Sci. III, 3491–3500. https://doi.org/10.1016/b0-12-226770-2/05861-0.
Rötzer, N., Schmidt, M., 2018. Decreasing metal ore grades-Is the fear of resource depletion justified? Resources 7, 1–14. https://doi.org/10.3390/resources7040088.
Rowland, C.A., 1999. Using the Bond work index to measure operating comminution efficiency. Miner. Metall. Process. 15, 32–36.
Saguru, C., Ndlovu, S., Moropeng, D., 2018. A review of recent studies into hydrometallurgical methods for recovering PGMs from used catalytic converters. Hydrometallurgy 182, 44–56. https://doi.org/10.1016/j.hydromet.2018.10.012.
Schulte, R.F., 2020. PLATINUM-GROUP METALS. U.S. Geol. Surv. Miner. Commod. Summ. January, 124–125.
Shaik, K., Petersen, J., 2017. An investigation of the leaching of Pt and Pd from cooperite, sperrylite and column bioleached concentrates in thiocyanate-cyanide systems. Hydrometallurgy 173, 210–217. https://doi.org/10.1016/j.hydromet.2017.08.021.
Shedd, K.B., 2020. Cobalt. U.S. Geol. Surv. Miner. Commod. Summ. January, 50–51. https://doi.org/10.1017/CBO9781107415324.004.
Shedd, K.B., McCullough, E.A., Bleiwas, D.I., 2017. Global trends affecting the supply security of cobalt. Min. Eng. 69, 37–42.
Spooren, J., Binnemans, K., Björkmalm, J., Breemersch, K., Dams, Y., Folens, K., González-Moya, M., Horckmans, L., Komnitsas, K., Kurylak, W., Lopez, M., Mäkinen, J., Onisei, S., Oorts, K., Peys, A., Pietek, G., Pontikes, Y., Snellings, R., Tripiana, M., Varia, J., Willquist, K., Yurramendi, L., Kinnunen, P., 2020. Near-zero-waste processing of low-grade, complex primary ores and secondary raw materials in Europe: technology development trends. Resour. Conserv. Recycl. 160, 2–18. https://doi.org/10.1016/j.resconrec.2020.104919.
Sverdrup, H., Ragnarsdottir, K.V., 2014. Natural resources in a planetary perspective. Geochemical Perspect. 3, 129–341. https://doi.org/10.7185/geochempersp.3.2.
Valero, A.A., Valero, A.A., Gómez, J.B., 2011. The crepuscular planet. A model for the exhausted continental crust. Energy 36, 694–707. https://doi.org/10.1016/j.energy.2010.09.034.
Valero, A.A., Domínguez, A., Valero, A.A., 2015. Exergy cost allocation of by-products in the mining and metallurgical industry. Resour. Conserv. Recycl. 102, 128–142. https://doi.org/10.1016/j.resconrec.2015.04.012.
Valero, A., Valero, A., 2012. Exergy of comminution and the Thanatia Earth's model. Energy 44, 1085–1093. https://doi.org/10.1016/j.energy.2012.04.021.
Valero, A., Valero, A., 2014. Thanatia: the destiny of the Earth's mineral resources. World Scientific Publishing, Zaragoza.
Valero, A., Valero, A., 2015. Thermodynamic Rarity and the Loss of Mineral Wealth. Energies 8, 821–836. https://doi.org/10.3390/en8020821.
Valero, A., Valero, A., Domínguez, A., 2013. Exergy Replacement Cost of Mineral Resources. J. Environ. Account. Manag. Abril 147–158. https://doi.org/10.5890/JEAM.2013.05.004.
Valero, A., Valero, A., Calvo, G., Ortego, A., 2018. Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. 93, 178–200. https://doi.org/10.1016/j.rser.2018.05.041.
Valero, A., Valero, A., Calvo, G., 2021. The material limits of the energy transition: Thanatia, 1st ed. Springer.
Wäger, P., Widmer, R., Stamp, A., 2011. Scarce technology metals: applications, criticalities and intervention options. Fed. Off. Environ. 09, 91.

Wei, W., Samuelsson, P.B., Jönsson, P.G., Gyllenram, R., Glaser, B., 2020. Energy Consumption and Greenhouse Gas Emissions of Nickel Products. Energies 13, 2–22. https://doi.org/10.1007/s11837-023-05707-8.

West, J., 2011. Decreasing Metal Ore Grades: Are They Really Being Driven by the Depletion of High-Grade Deposits? J. Ind. Ecol. 15, 165–168. https://doi.org/10.1111/j.1530-9290.2011.00334.x.

Wilburn, D.R., Bleiwas, D.I., 2004. Platinum-Group Metals: World Supply and Demand. U.S. Geol. Surv. Open-File Rep. 1224, 152.

Xiao, Z., Laplante, A.R., 2004. Characterizing and recovering the platinum group minerals - A review. Miner. Eng. 17, 961–979. https://doi.org/10.1016/j.mineng.2004.04.001.

Zhang, J., Tian, X., Chen, W., Geng, Y., Wilson, J., 2022. Measuring environmental impacts from primary and secondary copper production under the upgraded technologies in key Chinese enterprises. Environ. Impact Assess. Rev. 96, 2–9. https://doi.org/10.1016/j.eiar.2022.106855.