This is the accepted manuscript of an article published in Environmental Development.
The final version is available at: https://doi.org/10.1016/j.envdev.2021.100683

The influence of ore grade decline on energy consumption and GhG emissions: the case of gold

Guiomar Calvo*, José-Luis Palacios**, Alicia Valero*

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

** Departamento de Ingeniería Mecánica, Escuela Politécnica Nacional, Quito (Ecuador).

Abstract: With the rush of metal consumption in the last decades and the expected raw material demand driven by the clean and digital transition, a growing concern has emerged about the decline of ore grades. Research of the effect of ore grade decline on energy consumption during the processing of metals has conventionally been addressed using historical data and LCA analyses. This paper provides another approach using a computational model developed with specialized software, HSC Chemistry, to analyse this relationship using gold as a case study. Gold was selected as it is a precious metal widely used in various applications, from jewellery to electronic circuits and will be key for digitalizing the economy. Considering all mineral processing stages, it was verified that the specific energy and associated environmental impact would experience exponential growth as ore grade in the mines decreases. As one of the most energy intensive stages is comminution, fueled by electricity, the associated environmental impact is very much dependent on the electricity mix of the producing country. This approach allows for an evaluation of the future production's environmental impact for gold.

Keywords: Mineral resources, ore grade decline, gold, energy, environmental impacts

1. Introduction

For centuries, gold has been an icon of royalty and wealth. Since the chalcolithic, gold has been used in diverse applications, the oldest uses in coinage and jewellery. Currently, it is also used in electronic devices and medical applications (World Gold Council, 2021a). Gold has excellent properties; its electrical conductivity, corrosion resistance, and stability make it very useful for diverse applications. Gold is used in the form of electroplating coatings, connectors, wires, circuits, etc.

According to the World Gold Council[1], around 190.000 tonnes of gold have been mined from the Earth throughout history. From this, about two-thirds were extracted in the last few decades. This growing exponential trend is in line with the extraction of many other minerals, which, in some cases, have increased from three to even tenfold in just a few decades (Valero et al., 2015; Calvo et al. (2017b). Moreover, it is expected that around 50,000 metric tons of gold reserves globally could be mined in the future, considering current economic criteria (USGS, 2020).

---

[1] https://www.gold.org

In the last decades, gold mines have seen how the average ore grade has decreased. A situation that becomes even more dramatic when compared to the ore grade of the beginning of the 20th century. The energy associated with the mining industry is considerable and, as ore grade decreases, it is expected that more energy would be needed to extract, at least, the same amount of ore than before. Fortunately, technological improvements have allowed lower-grade mines to be exploited. Yet, according to Domínguez and Valero (2013), where historical data sets of 17 major gold producing countries were analysed, although progress in technology has been made, in most cases, energy requirements are increasing because the primary variable is the ore grade.

Taking this into consideration, the current paper analyses the relationship between ore grade and energy consumption based on a simulation of real operations. The main goal is to study how the energy required to extract gold could evolve if we had to rely only on low ore grade mines in the near future, using today's technology. To better understand the importance of this research, the past and current situation of gold extraction in the world is portrayed in section two. Then, in the third section, the methodological procedure to undertake this investigation is described. In the fourth section, the main results are outlined, accompanied by a comparison of the power delivered by two gas-power stations in one of the largest gold mines in the world. This shows the increase in energy to produce gold as the ore grade decreases in mines. Last, implications of the research are highlighted.

2. Past and present of gold extraction

Gold is one of the top four most expensive metals, along with palladium, platinum, and silver. Historically, South Africa has been the largest gold producer. However, mine production in the country has been gradually decreasing in recent years (Figure 1). Today, China, Russia, and Australia are the largest gold producers, with around 3,000 tonnes mined each year (USGS, 2020). That said, it is the South Deep gold mine, located near Johannesburg, South Africa, one of the world's largest and deepest mines. There, gold is mined underground, and reserves are estimated at around 32.8 Moz and resources at 60.1 Moz (Fields, 2019).

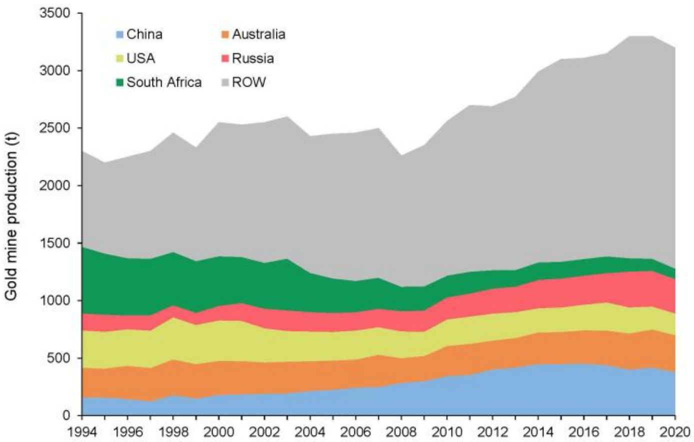


Figure 1. Gold production per country from 1994 to 2020 (USGS, 2020). ROW: rest of the world.

If we analyse the countries included in the "rest of the world" category, many of them are developing countries, such as Ghana, Brazil, or Mexico, regions whose economy heavily relies on mineral resource exports (Palacios et al., 2018).

Statistics of the World Gold Council (World Gold Council, 2021b) show that in 2017 the primary uses of gold were demanded mainly by the manufacture of jewellery (53%), 39% was used for financial purposes for investment and central banks, and 6% in electronics (Figure 2). However, the use of gold has also become very relevant in other sectors, such as in the electronic and automotive industries. For example, vehicles contain increasing amounts of electric and electronic equipment, which require gold (Ortego et al., 2020).

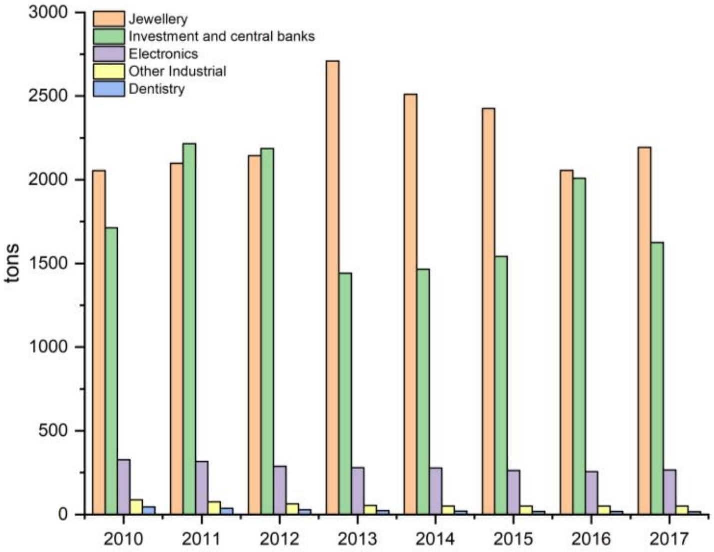


Figure 2. Historical demand for gold by sector (World Gold Council, 2021b)

Primary sources are not only relevant in the gold market. Secondary sources can provide not negligible amounts of gold ready to be used. Due to its properties and its high price, around one-third of gold is currently recycled. It comes vastly from jewellery products, as currently, the technology available to recover this metal from electronic applications is still minimal.

When metals end up in the Technosphere, their physical features change. For instance, gold becomes very complicated to recover in specific applications, where it is used in a dispersive manner, such as electronics present in a mobile phone or vehicles. Current gold mines have ore grades that range from 5 to 30 grams per ton, although the average is around 8 g/t (Valero and Valero, 2014). If we had a ton of mobile phones, the gold contained would be approximately 300 grams, around thirty times more than in mines. Yet this gold is not easily recoverable with current technologies. For this reason, this dispersive uses of minor metals force us to resort to primary extraction

As we rely on this primary extraction, gold exploration and ore grade evolution has been of high interest in the last few decades, given the relevance of this metal for the economy. As it happens with other elements, the period between discovery and exploitation of a deposit is getting wider with each passing decade, regardless of how the commodity's price has evolved. For instance, less than 30 new gold mines were discovered between 1985 and 1995, and they all began production at least 8 years later. In the next two decades, this number increased to 11 years and, from 2006 to 2013, to 18 years (SNL

Metals & Mining, 2014). Moreover, some studies show that this gap could reach even thirty years or more (Letwin, 2017).

To this, it can be added that some authors have demonstrated that the gold average ore grade in the mines is decreasing. For instance, Mudd (2007a) studied the evolution of the ore grade over time in mines located in Brazil, Australia, South Africa, Canada, and the United States. In all the countries, a clear declining tendency was observed. For instance, around 1950 in the United States, the average ore grade was 10 g/t. A few decades later, it barely reached 5 g/t (Mudd, 2007a). In South Africa, it went from 13 g/t in the 1970s to 5 g/t about thirty years later. Another paper focused only on Australian gold ore grade evolution, from mid-1850 to the beginning of the 20th century. The results showed a long-term decline in ore grade, combined with more open cut mines and a considerable increase of waste rock and tailings (Mudd, 2007b). This trend has also been observed in other metals, a situation caused by price changes, technological innovation, type of deposits mined, etc. (Mudd, 2007c).

A direct consequence of the decrease of the ore grade in the mines is that the energy needed for metal processing increases. In 1991, the average energy consumption of two gold mines was 172 GJ per kg of gold, while in 2006, for twenty-two mines investigated, it was 187 GJ/kg (Mudd, 2007a). This close relationship between ore grade and energy consumption has been proven in previous papers (Calvo et al., 2016; Domínguez and Valero, 2013).

As ore grade decreases, the mines are going to get closer to the concentration of the metal in bare rock a situation that could both compromise supply and have direct consequences of the environment due to increase energy consumption. For this reason, analysing how both factors interact with each other is crucial.

3. Methodology

Different scenarios must be assessed to understand better the influence that ore grade has on energy consumption, considering the different types of gold-bearing minerals and the corresponding processing routes. With the computational software HSC Chemistry-version 9.7.1 (Garcia et al., 2018), a model can be then developed to produce gold from a totally dispersed environment, the bare rock.

3.1. Extracting gold from bare rock

As mentioned before, ore grade decline is usually associated with more energy being consumed. Although extracting metals from common rocks is feasible, it would imply using much more energy (Skinner, 1976). Authors like Harmsen et al. (2013), Bardi (2014) or Norgate and Jahanshahi (2010) have supported this statement on the significant increase of specific energy for the extraction of metals from low-grade deposits. Steen and Borg (2002) estimated metal production from common rocks, reporting increments between one and two orders of magnitude for the production cost of metal concentrates, such as copper, cadmium, manganese, etc. Based on LCA analysis carried out in SimaPro and mathematical approximations, Norgate and Haque (2012) and Rankin (2011) also corroborated this exponential growth in the energy required to produce metals when ore grade decreases.

If gold average ore grade continues to decrease, we will reach a point where it could be hypothetically possible to obtain it from bare rock. This, in fact, constitutes our starting point for this study.

A previous model of dispersed crust was developed in Valero and Valero (2014). Thanatia, which represent a resource-exhausted planet named has no mineral deposists. All elements are in a dispersed state throughout the crust. Thanatia comprises 324 species, 292 minerals, and 32 diadochic elements. A complete description of the hypothesis behind Thanatia's crust composition and all the substances included can be found in Valero and Valero (2014).

As for gold, in Thanatia it is mainly found in native form ($1.21 \cdot 10^{-07}$ wt-%) and in tellurides, such as calaverite ($2.46 \cdot 10^{-08}$ wt-%) and sylvanite ($3.12 \cdot 10^{-08}$ wt-%). The sum of all of them can be considered the average ore grade of gold in Thanatia, which is $1.44 \cdot 10^{-03}$ g/t Au. This would be the worst-case scenario, equivalent to extracting gold from the bare rock. Once we know the concentration, we have to understand the current gold recovery processes.

3.2. Gold ore processing

The routes for metal production depend on the type of ore. Generally, gold can be obtained both in native form or in tellurides (Valero and Valero, 2014). In both cases, the comminution process is essential. In this process, the ore is reduced in size through crushers and mills until reaching an appropriate size in which the metal contained in the ore can be liberated (Lindroos and Keranen, 1985; Valero and Valero, 2012; Wills and Napier-Munn, 2006)

The specific energy in comminution can be calculated by applying Bond's equation (Skarin and Tikhonov, 2015; Wills and Napier-Munn, 2006) (equation 1):

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

Where W is the specific energy consumption of the mill (kWh/t), W_i is the work index measured in a laboratory mill (kWh/t), P80 and F80 are 80% of the product and feed passing sizes (μm), respectively. EF_x is the product of the Rowland efficiency factors, which depends on the mill, size, type of grinding circuit, etc. (King, 2001; Rowland, 2002, 1982; Skarin and Tikhonov, 2015; Wills and Napier-Munn, 2006).

The theoretical power drawn by the mill (kW) is determined by W x T, where T is the throughput tonnage (t/h) (Wills and Napier-Munn, 2006). A typical particle size after the comminution process is usually below 75 μm (Christine et al., 2014; Lipiec et al., 2016; Marsden and House, 1992).

The appropriate route for gold processing in the case of native gold is through gravity concentration due to its high density. Studies by Carrasco (2016) and Valdivieso et al. (1999) were considered. The extraction of gold from tellurides entails flotation and pyrometallurgical treatment (roasting). In this regard, literature by Elis and Deschênes (2016), Zhang et al. (2010), and flowsheets of telluride processing plants, such as Emperor mines in Fiji (Marsden and House, 1992) were examined. The recovery of the metal from native gold and tellurides was made with solvent extraction through cyanide leaching with a conventional process of carbon in pulp (CIP). Then, electrowinning was considered for the recovery of gold from the leaching solution. Studies conducted by Sen (2010), Muir et al. (1985), Beyuo and Abaka-Wood (2016), Brandon et al. (1987), and Adams (1994) were revised.

A simplified flow chart of the different routes for the processing of native gold and tellurides, the same used in our model, is shown in Figure 3.

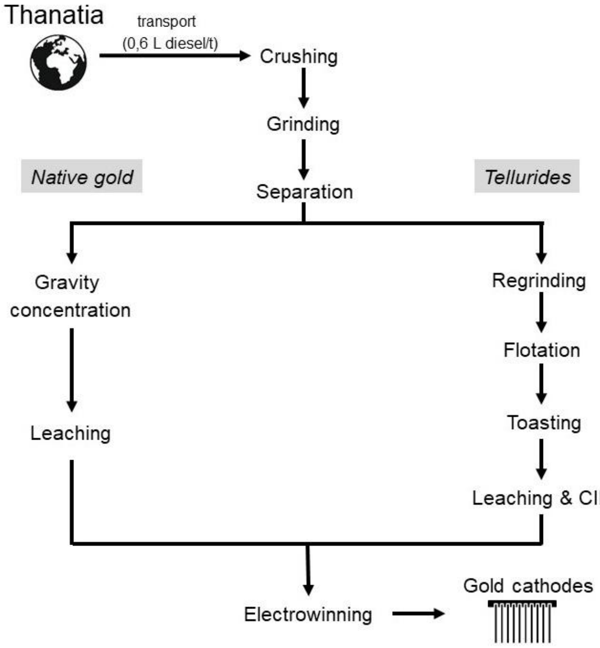


Figure 3. Simplified flowchart to produce gold in cathodes.

3.3. HSC Chemistry model

Once we have our baseline and the different recovery routes depending on the type of ore, a simulation can be carried out. Accordingly, our model was developed to study the behaviour of the specific energy required to produce gold by varying the ore grade.

For this study, we will consider that the ore grade will vary from the current average ore grade in the mines to the concentration of gold found in common rocks (i.e. Thanatia). Besides, assuming that this hypothetical mine and its correspondent processing plant could be located in any region, environmental impacts will be estimated for different countries and energy mixes using GaBi software, version 8.7.0.18 and database 8007 (Thinkstep AG, 2018).

The computational model in HSC Chemistry was developed based on the study of different flowsheets, especially for telluride ores, technical papers (Ellis and Deschênes, 2016; Marsden and House, 1992; Valdivieso et al., 1999; Zhang et al., 2010), and publications of modeling in HSC (Abadías Llamas et al., 2019; J.-L. Palacios et al., 2019; J. Palacios et al., 2019a). In particular, in Palacios et al. (2019b), a model in HSC was developed to produce gold from Thanatia.

To confirm the validity of the model, results were compared with those published in the literature. For example, Chapman and Roberts (1983) and Ballantyne et al. (2014)

reported comminution values for gold ranging between 15 kWh/t-Au to 20 kWh/t-Au, which were within the same range of the results of the model. The retention time, which can vary from 5 to 30 minutes (Fuerstenau et al., 2007; Lindroos and Keranen, 1985; Lu, 2015),, was another parameter for validation. All values obtained in the model were within this order of magnitude.

To better assess the ore grade evolution over time, the model was properly modified to change the concentration of gold. First, Thanatia was considered as the reference state for the ore's chemical composition from which gold is extracted. As the starting point, an initial concentration of $1.44 \cdot 10^{-03}$ g/t Au was used, as reported in Valero and Valero (2014). Then, the concentration of gold was increased until a conservative scenario with an average representative concentration of 2.72 g/t Au. This number comes from a literature review from the analysis of ore grade in different copper deposits and Ecoinvent 2007 database (Calvo et al., 2016; Comisión Chilena del Cobre, 2015; Northey et al., 2014).

Due to the considerable number of assumptions to simulate gold production from Thanatia, only the main ones are summarised in this paper. The rest can be found in a previous study (Palacios et al. 2019b). The consumption of energy, particularly diesel, used for ore-handling, meaning the transport of material from the mine to the production site, is significant and cannot be disregarded. According to some studies, it can account for 17% to 40% of the total embodied energy (Australian Government, 2011; Rankin, 2012, 2011). In our model, for ore-handling, fuel consumption was assumed to be 0.6 l/ton of rock as suggested in Calvo et al. (2016). Still, as Thanatia's composition is homogeneous, it was assumed that the production site is located as close as possible to the mine, so tonnage prevails over distance. Furthermore, due to the dispersed state of minerals in Thanatia, it was treated as a complex ore. Therefore, the input ore in the model was assumed at 6,000 tons per hour.

The concentration process consists of comminution (crushing, grinding, and re-grinding), gravity concentration, and flotation. The specific energy during comminution was calculated with Equation 1. The 80% passing size of the feed (F80) and the product (P80) for every crusher and mill were obtained directly from the HSC model. As previously explained, the work index has a direct influence on the specific energy. Since Thanatia is a complex-ideal ore, and a single value for its hardness cannot be readily determined, a range of values for the work index (Wi) from 3 to 42 kWh/t were considered (Weiss, 1985). Not considering a single value for Wi constitutes a difference with other author's approaches to estimate the specific energy (Calvo et al., 2017).

Because of the high density of gold, only gravity concentration is necessary for the native gold stream (Carrasco, 2016; Valdivieso et al., 1999; Wills and Napier-Munn, 2006). Manufacturers data regarding the gravity concentrator's energy consumption of 75 kW for capacity between 45 t/h to 100 t/h were considered (Falcon, 2018). The next step is leaching, which seeks to dissolve partially a solid to recover the material contained in it, in our case, gold. The leaching liquid used can vary depending on the properties of the element in question. It may be an acid, a salt, etc. The process is carried out at lower temperatures compared to other metallurgical processes. In the last phase of the gold concentration process, cyanidation is used explicitly as a leaching technique, consisting of converting gold (insoluble in water) into soluble complexes by adding sodium cyanide.

For the gold associated with the tellurides, re-grinding is required to liberate as much gold as possible. The next step is flotation, concentrating the metal by injecting air bubbles into an aqueous medium. The mineral particles of interest remain attached to these air

This is the accepted manuscript of an article published in Environmental Development.
The final version is available at: https://doi.org/10.1016/j.envdev.2021.100683

bubbles, thanks to the addition of chemical reagents that promote or decrease metals hydrophobicity. The gold attached to the bubbles remains floating in the foam, generating a pulp that is then collected. This resulting pulp is concentrated in successive tanks until the maximum possible recovery state is reached. It then undergoes a roasting process at temperatures between 600 and 700ºC, ensuring the telluride bonds are broken and gold is released.

After the gold has been recovered from the different ores, the resulting material undergoes an electrometallurgical process. This process consists of the extraction and refining of metals using an electric current. During this electrolytic process, an electric current passes through the aqueous solution containing the gold. As a result, the metal slowly deposits on the cathode, creating the final product, gold cathodes (Norgate and Haque, 2012).

Norgate and Haque (2012) also published estimations of specific environmental impacts of gold production, reporting some figures for the specific consumption of energy. Natural gas consumption is assumed to be 0.35 GJ/t Au for roasting, 1.4kWh/t ore during leaching, and 3,100 kWh/t Au for electrowinning. The specific energy per ton of gold was estimated through the obtained flow rate from the model at each specific starting ore grade.

The model was appropriately set up, and the simulations were performed. An example of the simulation can be seen in Figure 4, where the crushing and grinding circuits in the comminution process are depicted.

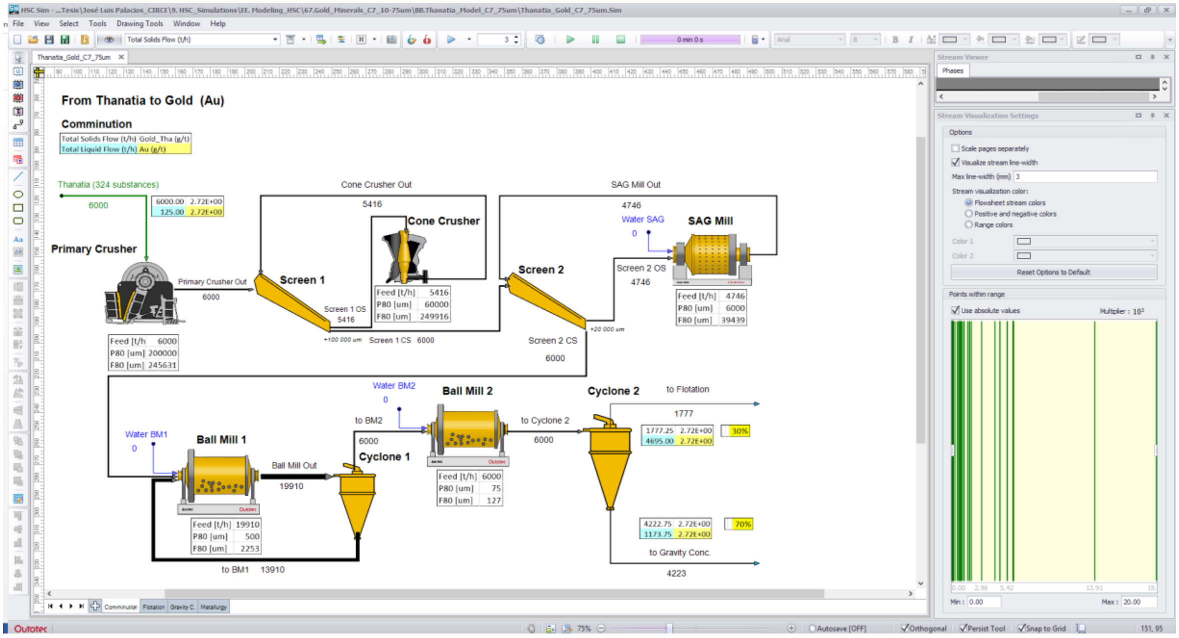


Figure 4. Screen capture of the simulation for the comminution process in HSC software.

3.4. Environmental impacts

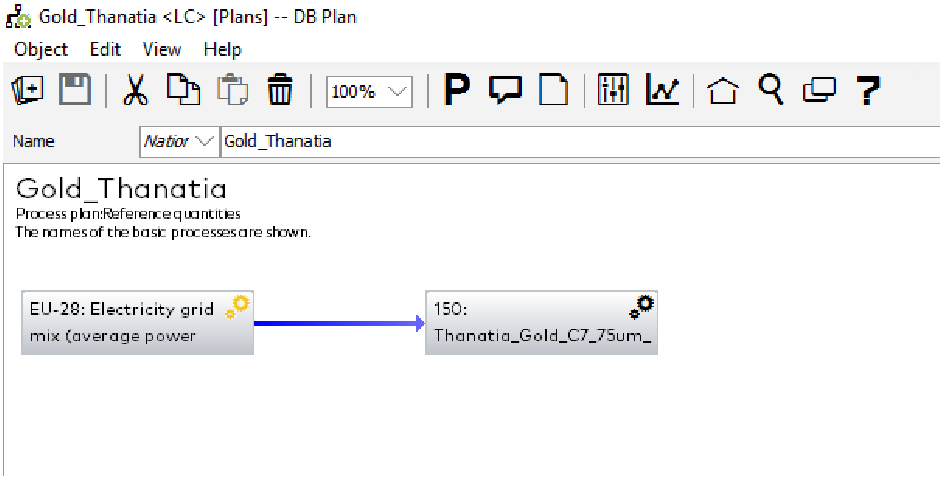
LCA methodology can evaluate the effects on the environment of a product by measuring the impacts of the corresponding fabrication process (ISO, 2006). Previously, LCA principles have been applied to assess gold production environmental effects for a general location, as described by Norgate and Haque (2012), and for China by Chen et al. (2018).

Nevertheless, none of these studies have gone more in-depth in the variables that intervene directly in the production process. For instance, the effect of the final size in comminution was never considered before. For this reason, in this work, through the direct export-import link between HSC and GaBi, the environmental impacts of the production of gold from Thanatia composition will also be evaluated.

The assessment of impacts is mainly associated with electricity during comminution as it accounts for the highest energy consumption during the production processes. In addition, the LCA tool in HSC software allows analysing the life cycle inventory (LCI), a previous LCA stage where an inventory of inputs and outputs is created. The LCA tool in HSC enables to export an Ecospold file that can be imported in GaBi.

Thanatia is a global model for crustal composition. Still, the electricity mix of each region can significantly vary. For this reason, a comparative analysis between fictitious gold deposits placed in five different continents was carried out to understand better the impact that a mine extracting gold from bare rock in each region could have on the environment.

Europe, Asia, North America, South America, and Africa were the chosen continents. In each one, a representative country was chosen. Then, the electricity mix of each country was interlinked with the process imported from HSC. Figure 5 shows the connection of the introduced production process from HSC with the electricity mix to later evaluate some of the environmental impacts with GaBi.



Name: Gold_Thanatia

Gold_Thanatia
Process plan:Reference quantities
The names of the basic processes are shown.

Figure 5. Screen capture of GaBi to assess some environmental impacts of the production process imported from HSC.

GaBi software, version 8.7.0.18, and database 8007 were used for this analysis (Thinkstep AG, 2018). The environmental impact categories investigated were air pollution through global warming potential (GWP), acidification potential (AP) and photochemical ozone creation potential (POCP), and for water pollution, eutrophication potential (EP).

4. Results

Results of the simulation and further data processing to obtain the specific energy to produce gold are shown in Table 1. As stated in the methodology section, to obtain these data, the concentration of 2.72 g/t was used, assuming an 80% passing (P80) size at the end of comminution. Additionally, a representative work index (Wi) of 15 kWh/t was considered.

Table 1. Results for Wi=15 kWh/t and P80 final size of 75 µm for an ore grade of 2.72 g/t-Au.

Process	Specific Energy (GJ/t-Au)
Ore-handling	$8.53 \cdot 10^{-03}$
Concentration	$2.39 \cdot 10^{+04}$
Roasting	$3.50 \cdot 10^{-01}$
Leaching	$7.68 \cdot 10^{+03}$
Cyanidation	$1.85 \cdot 10^{+03}$
Electrowinning	$9.57 \cdot 10^{+03}$
TOTAL	$\mathbf{4.20 \cdot 10^{+04}}$

Table 1 shows that 57% of the total energy to produce gold corresponds to the concentration process (comminution, gravity concentration, and flotation). The corresponding power draw and specific energy are shown in Table 2. It can be observed that more than 90% of the energy is consumed by the comminution process (crushing and grinding). To validate the results from our model in HSC, the specific energy during this process was compared with values reported in the literature.

Table 2. Power draw and specific energy for comminution, gravity concentration and flotation for Wi=15 kWh/t and P80 final size of 75 µm for an ore grade of 2.72 g/t-Au.

Stage	Power Demand (MW)	Specific Energy (kWh/t-ore)
Comminution	102	17.0
Gravity concentration	4	0.7
Flotation	2	0.4
TOTAL	108	18.0

The specific energy for comminution was in the same range as those values reported by Chapman and Roberts (1983) and Ballantyne et al. (2014).

In Figure 6, the horizontal axis represents time, from the present (right) to the future (left). To obtain these specific energy values, the following processes were considered: ore-handling, concentration (comminution and gravity concentration), roasting, leaching, cyanidation, and electrowinning. For a more representative analysis, different ore grades were included: from 1.44-03 g/t Au to 2.72 g/t Au. This same process was also done for the work index (from Wi=5 to 42 kWh/t) and final particle size (from 10 to 75 µm).

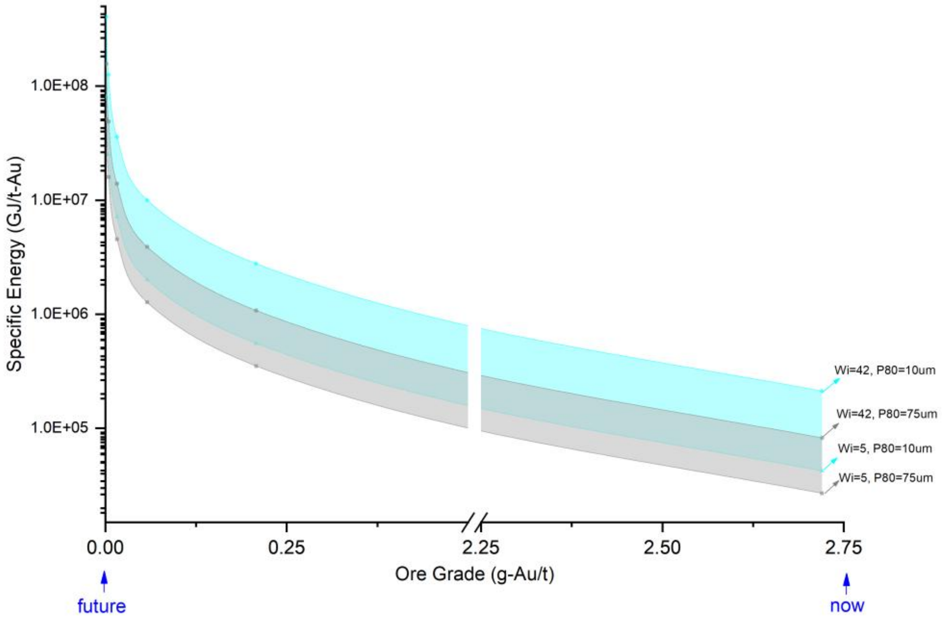


Figure 6. Specific energy to produce gold from 1.44-03 g/t Au to 2.72 g/t Au, varying the work index (Wi) and final size in comminution (P80).

As expected, the specific energy range is higher when the work index (Wi) and the final size (P80) increases. This increase can be observed when Wi goes from 5 to 42 kWh/t, even if the final size of the particles in P80 remains constant, and vice versa. Additionally, an exponential trend can be observed. The specific energy increases when the ore grade of the deposit decreases. In the same way, when the particle size decreases, the specific energy for processing increases. That is why the band of specific energy is wider for P80 of 10 µm rather than 75 µm, and the former overlaps the latter.

To better understand the implications of the model developed in this paper, we will assume that our gold processing plant will have the same gold production as the Pueblo Viejo mine in 2018. Pueblo Viejo is the fourth world's biggest gold mine and is located in the Dominican Republic (Statista, 2020). In 2018, its production reached approximately 30 tons of gold (Stewart, 2019). The mine has two central power stations that run in a combined cycle with natural gas and/or liquid fossil fuel to meet its energy requirements. The power stations, Quisqueya I and II, have an installed capacity of 156 MW and 220 MW, respectively. The total annual energy production of Quisqueya I and II in 2018 was 1.21 TWh and 1.41 TWh, respectively (Comisión Económica para América Latina y el Caribe (CEPAL), 2019).

A comparison can then be carried out between the total energy required to produce gold (in TWh) in the model and the annual production of energy of Quisqueya I and II in 2018. We will consider Wi=5 kWh/t and 80% final particle size of 75 µm.

Under these conditions, considering 2.72 g-Au/t as the starting point of the ore grade in our mine, the total energy required to produce these 30 tons of gold would be 0.35 TWh. However, as stated before, ore grade in mines is decreasing over time. According to our model, if the ore grade decreases one order of magnitude (to $7.51 \cdot 10^{-1}$ g-Au/t), the total energy to produce that same amount of metal would be 1.28 TWh. We must note that this value is almost equal to the total annual energy production of Quisqueya I.

On the other hand, if the ore grade decreases two orders of magnitude (to $5.76 \cdot 10^{-2}$ g-Au/t), the total energy needed would be 16.68 TWh, meaning six times more than the total annual production of energy of Quisqueya I and II combined. In other words, if the ore grade of gold decreased two orders of magnitude, six power plants with the capacity of Quisqueya I and II would be needed to meet the energy requirements.

Last, if ore grade continues to decrease over time, to three orders of magnitude less (to $4.59 \cdot 10^{-3}$ g-Au/t), according to the scenario presented in Figure 6, the energy required would be 672 TWh approximately. This means that more than 200 power plants like Quisqueya I and II would be required. However, these numbers have been obtained using a very soft ore and particles with a larger final size. Therefore, numbers of specific energy could double for harder ores (Wi=42 kWh/t) and with finer particle sizes. With this example, we can see that the decline in ore grade in gold mines could soon reach a point where gold production becomes unaffordable from an energy perspective.

Let us now analyse the environmental impact associated with gold mining. As we have seen, comminution represents the most intensive energy consumer process extracting gold from Thanatia. Thus, the electricity mix composition will directly influence the number of pollutants released into the environment.

Figure 7 shows the environmental impact categories for an ore grade of 2.72 g/t Au, work index (Wi) of 15 kWh/t, and assuming an 80% passing (P80) size at the end of comminution of 75 μm.

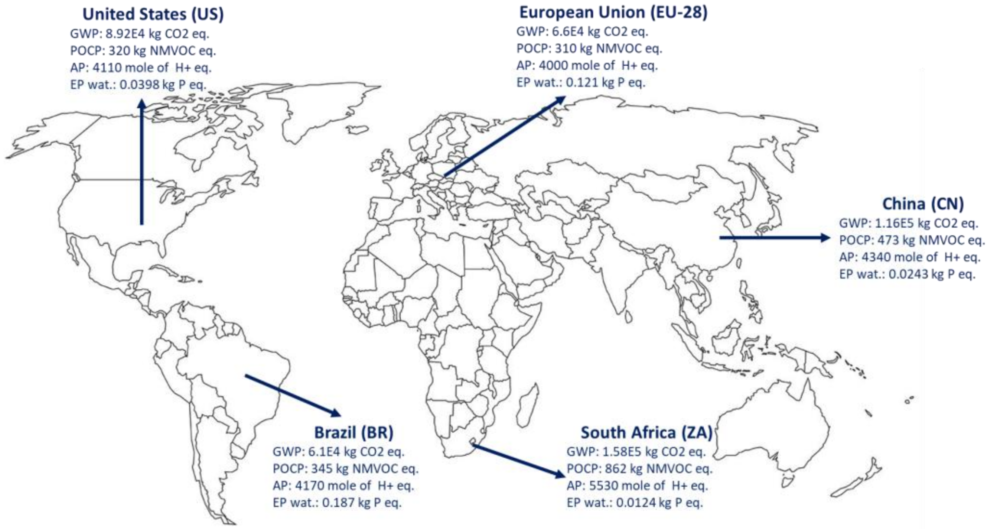


Figure 7. Main environmental impact categories in different locations for 2.72 g/t Au, work index 15 kWh/t and P80 at the end of comminution of 75 μm.

The largest GWP values occur in South Africa, with $1.58 \cdot 10^5$ kg of CO_2 eq, followed by China, while the lower values are for the European Union and Brazil, with one order of magnitude lower. As stated before, these differences mainly depend on the composition of the electricity mix of each country.

According to statistics of the International Energy Agency (IEA), in 2016, 90% and 68% of the primary electricity production came from coal in South Africa and China, respectively. This situation is entirely different in industrialised countries. In the United States, 33% of the electricity was produced by burning natural gas and 31% burning coal.

As for the European Union, 23% of the electricity was generated by coal-firing power plants. Still, other energy sources have more relevance in other countries. For instance, hydroelectricity represented approximately 76% of Brazil's total electricity (International Energy Agency (IEA), 2018).

With the current energy mix of industrialised countries, emissions will grow proportionally to the energy consumption as ore grades decline. This means that the environmental impact of mining will undoubtedly spiral up. One needs to add that reducing ore grades means extracting exponentially more amount of waste rock that need to be transported with huge trucks currently fuelled by diesel. It is unlikely that trucks will become electrified, at least in the medium term, leading to an increased emission of CO_2 and other pollutants in the mining areas. Additionally, this transport will also lead to an increase in the dust produced, affecting nearby regions.

5. Discussion and conclusions

With each passing decade, humanity demands more materials to satisfy its growing needs. As a result, mines become increasingly exhausted, with ore grades rapidly declining. This issue will become even more acute with the expected deployment of clean technologies required for the energy transition. Gold is not an exception since, in addition to the traditional uses for gold, it is increasingly found in electric and electronic equipment, which is key for the digital and clean economy.

The reduction of ore grades is generally associated with increased energy consumption, even if improvements in technology might partially offset these higher costs. Since nowadays, most of the energy consumed in mining and refining operations is fossil-fuel based, emissions from the mining industry are likely to spiral up as demand increases and ore grade declines. The clean energy transition, which seeks for drastically reducing GhG emissions, might face a rebound effect if this issue is not taken seriously.

As we analysed in this paper for gold, energy increases exponentially with lower ore grades, making the further exploitation of the deposits unpayable at one point. The most energy intensive process is comminution (crushing and grinding), which is carried out with electricity. Therefore, the origin of the electricity used is of paramount importance in the impacts associated with mining. Accordingly, depending on the country where minerals are extracted, the environmental impacts can significantly vary. This could, in turn, increase the socio-environmental burden on developing countries. As analysed in this paper, the effect of ore grade decline is much more harmful in South Africa or China than in the European Union or Brazil due to their current electricity mix. Furthermore, the economy of many developing countries relies on natural resource extraction, which could worsen the situation. Electrification of the mining industry, i.e., using electric trucks and other machinery currently fuelled mostly with diesel, would also help decarbonise the mining industry as long as it comes from renewable sources.

Curbing mining emissions can also be reached by resorting to secondary sources, which comparatively, require less energy per refined commodity. Unfortunately, recycling rates are still low for many minor but key metals for the energy and digital transition. This can be attributed, among others, to the still very low collection rates or the chemical complexity of products requiring not yet developed recycling processes. Substitution of scarce elements by abundant ones can be an additional solution. That said, substitution is a viable option for some applications, but not for all. As seen in this paper, gold is primarily used in jewellery and it is improbable that other metals can totally substitute it.

In a similar way, it is very unlikely that another metal substitutes gold as a store of value. Therefore, it is in electronics and industrial uses where gold could be substituted for other metals. Palladium, silver or copper could be possible candidates. Still, their properties (resistance to corrosion, oxidation, conductivity, reliability, etc.) are not equivalent and this could lead to problems related to performance (Goodman, 2002). Currently, gold remains the only suitable material for many of these applications and in cases of crisis, such as the one caused by COVID-19, restricted sources can lead to problems in the supply chain (Althaf and Babbitt, 2021).

We must understand that gold is not an exception. There are many other metals and elements whose extraction is exponentially increasing since the last few decades. For this reason, similar simulations could be performed in future research for other minerals. The aim would be to detect how the increasing raw material demand, mostly driven by the deployment of new clean and digital technologies might slow down the efforts towards decarbonising the economy. As we saw in this paper, the depletion of worldwide deposits will require more energy and, hence, more emissions. Understanding this behaviour is key to search for more sustainable metal production routes. Additionally, with the help of HSC Chemistry software, it could be possible to promote strategies related to reducing energy consumption and associated environmental impacts in the mining industry, identifying which processes consume more polluting reagents, more energy or release more emissions."

In this regard, further studies could include analysing a distinct mine with a fixed mineral composition in which the gold ore grade decline can be studied along with information about the energy consumption. The advantage of working with a specific composition would be the reduction of the complexity of the model. Additionally, the computational model used in this paper could be applied to analyse the evolution of ore grade and energy consumption for other commodities.

6. Acknowledgments

We thank the National Secretary of Science and Education of Ecuador (SENESCYT), Prof. Dr. Oscar Restrepo of Universidad Nacional de Colombia for providing valuable bibliography and Ivan Fernandes, from the Helmholtz Institute Freiberg for Resource Technology for the revision of the first versions of this paper. Part of this study has been carried out under the ENE2017-85224-R project, financed by the Spanish Ministry of Economy, Industry and Competitiveness.

7. References

Abadías Llamas, A., Valero Delgado, A., Valero Capilla, A., Torres Cuadra, C., Hultgren, M., Peltomäki, M., Roine, A., Stelter, M., Reuter, M.A., 2019. Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production. Miner. Eng. 131, 51–65. https://doi.org/10.1016/j.mineng.2018.11.007

Adams, M.D., 1994. Removal of cyanide from solution using activated carbon. Miner. Eng. 7, 1165–1177. https://doi.org/10.1016/0892-6875(94)90004-3

Althaf, S., Babbitt, C.W., 2021. Disruption risks to material supply chains in the electronics sector. Resour. Conserv. Recycl. 167, 105248. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105248

Australian Government, 2011. Analyses of Diesel Use for Mine Haul and Transport Operations

[WWW Document]. Dep. Resour. Energy Tour. URL http://energyefficiencyopportunities.gov.au/industry-sectors/mining/ (accessed 2.25.18).

Ballantyne, G.R., Powell, M.S., 2014. Benchmarking comminution energy consumption for the processing of copper and gold ores. Miner. Eng. 65, 109–114. https://doi.org/10.1016/j.mineng.2014.05.017

Bardi, U., 2014. Extracted. How the quest for mineral wealth is plundering the planet. Club of Rome., United States of America.

Beyuo, M., Abaka-Wood, G.B., 2016. ZADRA Elution Circuit Optimisation and Operational Experience at the CIL Plant of Gold Fields Ghana Limited. 4th UMaT Bienn. Int. Min. Miner. Conf. 161–167.

Brandon, N.P., Mahmood, M.N., Page, P.W., Roberts, C.A., 1987. The direct electrowinning of gold from dilute cyanide leach liquors. Hydrometallurgy 18, 305–319. https://doi.org/10.1016/0304-386X(87)90072-7

Calvo, G., Mudd, G., Valero, Alicia, Valero, Antonio, 2016. 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, Alicia, Valero, Antonio, 2017. Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe. J. Ind. Ecol. 00, 1–14. https://doi.org/10.1111/jiec.12624

Carrasco, O.H., 2016. Concentración gravimétrica de menas auríferas. Rev. Met. 38, 38–50.

Chapman, P.F., Roberts, F., 1983. Metal resources and energy. Butterworths & Co, Butterworths.

Chen, W., Geng, Y., Hong, J., Yang, D., Ma, X., 2018. Life cycle assessment of gold production in China. J. Clean. Prod. 179, 143–150. https://doi.org/10.1016/j.resconrec.2018.07.028

Christine, B., Fleury, D., Fortin, A., Brisson, T., Joncas, L., 2014. Éléonore Gold Project Quebec , Canada NI 43-101 Technical Report. Québec, Canada.

Comisión Chilena del Cobre, 2015. Anuario de Estadísticas del Cobre y otros minerales 1996-2015.

Comisión Económica para América Latina y el Caribe (CEPAL), 2019. Estadísticas de producción de electricidad de los países del Sistema de la Integración Centroamericana (SICA). Datos preliminares a 2018. Ciudad de México.

Domínguez, A., Valero, A., 2013. GLOBAL GOLD MINING: Is technological learning overcoming the declining in ore grades? J. Environ. Account. Manag. 1, 85–101. https://doi.org/10.5890/JEAM.2012.01.007

Ellis, S., Deschênes, G., 2016. Treatment of Gold e Telluride Ores, in: Adams, M.D. (Ed.), Gold Ore Processing. Elsevier B.V., Singapore, pp. 919–926. https://doi.org/10.1016/B978-0-444-63658-4.00051-7

Falcon, 2018. Falcon Continuos Concentrators [WWW Document]. URL http://seprosystems.com/wp-content/uploads/2016/08/Falcon_C_Concentrator_2018.pdf (accessed 6.7.17).

Fields, G., 2019. Mineral Resources and Mineral Reserves Supplement to the Integrated Annual Report.

Fuerstenau, M.C., Jameson, G.J., Yoon, R.-H., EBSCOhost., 2007. Froth flotation : a century of innovation. Society for Mining, Metallurgy, and Exploration, Littleton, Colorado USA 80127.

Garcia, A., Remes, A., Roine, A., Karki, B., Vilaev, D., Sherstha, D., 2018. HSC Chemestry 9.

Goodman, P., 2002. Current and future uses of gold in electronics. Gold Bull. 35, 21–26.

https://doi.org/10.1007/BF03214833

Harmsen, J.H.M., Roes, A.L., Patel, M.K., 2013. The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. Energy 50, 62–73. https://doi.org/10.1016/J.ENERGY.2012.12.006

International Energy Agency (IEA), 2018. Statistics | Electricity generation by fuel (chart) [WWW Document]. IEA World Energy Balanc. 2018. URL https://www.iea.org/statistics/?country (accessed 11.27.18).

ISO, 2006. International Organization for Standarization 14040 Environmental Management-Life Cycle Assessment-Principles and Framework. London.

King, R.P. (Ronald P., 2001. Modeling and simulation of mineral processing systems. Butterworth-Heinemann.

Letwin, S.J.J., 2017. Growth in a time of reckoning. The need for sustainable gold replacement strategies. IAMGOLD Corporation.

Lindroos, E.W., Keranen, C.U., 1985. 5. Plants Using Flotation in the Concentration of Iron Ore, in: Weiss, N.L. (Ed.), SME Mineral Processing Handbook. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engine, New York, USA, pp. 20-22-20–33.

Lipiec, I., Braown, J., Allard, S., Masala, C., Searston, S., Watts, B., Sepúlveda, A., 2016. Fruta del Norte Project Ecuador NI 43-101 Technical Report on Feasibility Study. Vancouver, Canada.

Lu, L., 2015. Iron ore: Mineralogy, processing and environmental sustainability, Iron Ore: Mineralogy, Processing and Environmental Sustainability. Elsevier, Oxford, United Kingdom. https://doi.org/10.1016/C2013-0-16476-8

Marsden, J., House, C., 1992. The Chemistry of gold extraction. Ed. Ellis Horwood Limited., 2nd ed, Society for Mining, Metallurgy, and Exploration, Inc. Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, Colorado USA 80127.

Mudd, G.M., 2007a. Global trends in gold mining: Towards quantifying environmental and resource sustainability. Resour. Policy 32, 42–56. https://doi.org/10.1016/j.resourpol.2007.05.002

Mudd, G.M., 2007b. Gold mining in Australia: linking historical trends and environmental and resource sustainability. Environ. Sci. Policy 10, 629–644. https://doi.org/10.1016/J.ENVSCI.2007.04.006

Mudd, G.M., 2007c. An analysis of historic production trends in Australian base metal mining. Ore Geol. Rev. 32, 227–261. https://doi.org/10.1016/J.OREGEOREV.2006.05.005

Muir, D.M., Hinchliffe, W., Tsuchida, N., Ruane, M., 1985. Solvent elution of gold from C.I.P. carbon. Hydrometallurgy 14, 47–65. https://doi.org/10.1016/0304-386X(85)90005-2

Norgate, T., Haque, N., 2012. Using life cycle assessment to evaluate some environmental impacts of gold production. J. Clean. Prod. 29–30, 53–63. https://doi.org/10.1016/j.jclepro.2012.01.042

Norgate, T., Jahanshahi, S., 2010. Low grade ores – Smelt, leach or concentrate? Miner. Eng. 23, 65–73. https://doi.org/10.1016/J.MINENG.2009.10.002

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

Ortego, A., Calvo, G., Valero, Alicia, Iglesias-Émbil, M., Valero, Antonio, Villacampa, M., 2020. Assessment of strategic raw materials in the automobile sector. Resour. Conserv. Recycl. 161.

Palacios, J.-L., Fernandes, I., Abadias, A., Valero, Alicia, Valero, Antonio, Reuter, M.A., 2019. Avoided energy cost of producing minerals: The case of iron ore. Energy Reports 5, 364–374. https://doi.org/10.1016/J.EGYR.2019.03.004

Palacios, J., Abadias, A., Valero, Alicia, Valero, Antonio, Reuter, M.A., 2019a. The energy needed to concentrate minerals from common rocks: the case of copper ore. Energy 181, 494–503. https://doi.org/10.1016/j.energy.2019.05.145

Palacios, J., Abadias, A., Valero, Alicia, Valero, Antonio, Reuter, M.A., 2019b. 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

Palacios, J.L., Calvo, G., Valero, A., Valero, A., 2018. Exergoecology assessment of mineral exports from Latin America: Beyond a tonnage perspective. Sustain. 10. https://doi.org/10.3390/su10030723

Rankin, J., 2012. Energy Use in Metal Production. High Temp. Process. Symp. 2012 7–9.

Rankin, W.J., 2011. Minerals , Metals and Sustainability. CSIRO, Collingwood, Australia.

Rowland, C.A., 2002. Selection of rod mills, ball mills, pebble mills, and regrind mills, in: Mular, A.L., Bhappu, R.B. (Eds.), Mineral Processing Pland Desig, Practice, and Control. Proceedings. Society for Mining, Metallurgy, and Exploration Inc., Littleton, Colorado USA 80127, pp. 710–728.

Rowland, C.A., 1982. Selection of rod mills, ball mills, pebble mills, and regrind mills, in: Mular, A.L., Jergensen, G. V. (Eds.), Design and Installation of Comminution Circuits. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Littleton, Colorado USA 80127, pp. 393–438.

Sen, S., 2010. Gold recovery by KC from grinding circuit of Bergama CIP plant 63, 539–545. https://doi.org/10.1590/S0370-44672010000300017

Skarin, O.I., Tikhonov, N.O., 2015. Calculation of the Required Semiautogenous Mill Power based on the Bond Work Indexes. Eurasian Min. 1, 5–8.

Skinner, B.J., 1976. A Second Iron Age Ahead? The distribution of chemical elements in the earth's crust sets natural limits to man's supply of metals that are much more important to the future of society than limits on energy. Am. Sci. 64, No.3, 258–269.

SNL Metals & Mining, 2014. Strategies for Gold Reserves Replacement.

Statista, 2020. Chart: The World's Biggest Gold Mines | Statista [WWW Document]. World's Biggest Gold Mines. URL https://www.statista.com/chart/23053/gold-mines-by-tonnes-produced-annually/ (accessed 2.17.21).

Steen, B., Borg, G., 2002. An estimation of the cost of sustainable production of metal concentrates from the earth's crust. Ecol. Econ. 42, 401–413. https://doi.org/10.1016/S0921-8009(02)00123-4

Stewart, R., 2019. La Industria Minera Dominicana en 2018. GEONOTICIAS 16, 12–21.

Thinkstep AG, 2018. GaBi ts.

USGS, 2020. Mineral Commodity Summaries 2020. United States Geological Service.

Valdivieso, A.L., Amaya Ibarra, A., Oliva Rangel, S., Reyes Bahena, J.L., 1999. Concentracion Gravimetrica Centrifuga, in: XXIII Convención AIMMGM. Acapulco, México, pp. 1–12.

Valero, Alicia, Valero, Antonio, 2014. Thanatia: the destiny of the Earth´s mineral resources. A thermodynamic cradle-to-cradle assessment. World Scientific Press, Singapore.

Valero, Alicia, Valero, Antonio, Calvo, G., 2015. Using thermodynamics to improve the resource efficiency indicator GDP / DMC. "Resources, Conserv. Recycl. 94, 110–117. https://doi.org/10.1016/j.resconrec.2014.12.001

Valero, Alicia, Valero, Antonio, Gómez B., J., 2011. The crepuscular planet. A model for the exhausted continental crust. Energy 36, 694–707. https://doi.org/10.1016/j.energy.2010.07.017

Valero, Antonio, Valero, Alicia, 2014. Thanatia: the destiny of the Earth's mineral resources: A thermodynamic cradle-to-cradle assessment. World Scientific Press, United Kingdom.

Valero, Antonio, Valero, Alicia, 2012. Exergy of comminution and the Thanatia Earth's model. Energy 44, 1085–1093. https://doi.org/10.1016/j.energy.2012.04.021

Weiss, N.L., 1985. SME Handbook of mineral processing. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engine, New York, USA.

Wills, B.A., Napier-Munn, T., 2006. Will's Mineral Processing Technology: An introduction to the practical aspects of ore treatment and mineral.

World Gold Council, 2021a. New uses for gold [WWW Document]. New uses gold. URL https://www.gold.org/about-gold/gold-demand/sectors-of-demand/uses-of-gold (accessed 11.19.18).

World Gold Council, 2021b. Gold Demand by Country , Gold Demand and Supply Statistics, Goldhub [WWW Document]. Gold supply demand Stat. URL https://www.gold.org/goldhub/data/gold-supply-and-demand-statistics (accessed 11.19.18).

Zhang, J., Zhang, Y., Richmond, W., Wang, H.P., 2010. Processing technologies for gold-telluride ores. Int. J. Miner. Metall. Mater. 17, 1–10. https://doi.org/10.1007/s12613-010-0101-6