Energy Reports 5 (2019) 364–374

Contents lists available at ScienceDirect

Energy Reports

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

Research paper

Avoided energy cost of producing minerals: The case of iron ore

Jose-Luis Palacios [a,*], Ivan Fernandes [b], Alejandro Abadias [b], Alicia Valero [c], Antonio Valero [c], Markus A. Reuter [b]

[a] Departamento de Ingeniería Mecánica, Escuela Politécnica Nacional, Ladrón de Guevara E11-25, Quito 170517, Ecuador
[b] Helmholtz Institute Freiberg for Resource Technology, Chemnitzer Str. 40, 09599 Freiberg, Germany
[c] Research Centre for Energy Resources and Consumption (CIRCE) - Universidad de Zaragoza, CIRCE Building – Campus Río Ebro, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 15 October 2018
Received in revised form 20 February 2019
Accepted 7 March 2019
Available online xxxx

Keywords:
Iron
Mining
Metallurgy
Energy consumption
Thanatia
Exergy replacement cost

ABSTRACT

There is growing concern about the decline of the ore grade in mines and the increased energy usage for processing and refining metals. In the limit, where no concentrated deposits exist, minerals must be obtained from bare rock. A method for quantitatively assessing the “free bonus” granted by nature in providing concentrated minerals in mines and thus assessing the quality of the different resources is estimating how much energy is needed to concentrate the minerals, as they are already in mines, from bare rock. This bonus granted by nature reduces the costs of human mining and metallurgical processes, as well as the mining effort required of future generations. In this study, the concentration of high-iron-content minerals in common rocks was investigated via a computational model developed using the HSC software. As expected, the range of results for the specific energy for the concentration of iron from common rocks was considerably higher than the energy required by modern processes. This reveals the need to value current iron deposits and the challenge of developing sustainable methods of metal production to satisfy the needs of the present and future generations.

1. Introduction

The development of nations has required an enormous amount of materials, with metals being essential, and nature has suffered the consequences. Concern regarding the decline of high-ore-grade deposits has been expressed by many authors, such as Mudd Mudd (2007a,b, 2008, 2007c, 2010), Craig et al. Craig et al. (2014), Norgate Norgate and Jahanshahi (2010), and Calvo et al. Calvo et al. (2016). Even though iron is one of the most abundant minerals in Earth’s crust Skinner (1979), the rich deposits have already been exploited owing to the massive consumption of metals by humans. Thus, new deposits must be found in remote locations, and the energy expenditure for not only handling the ore but also processing metals has increased Calvo et al. (2016). Steel – a carbon–iron alloy – is fundamental in the modern world. Although iron has one of the highest recycling rates among metals Graedel et al. (2011), in 2015, iron-ore production was 2.2 billion tons, which is 233% higher than that in 1990 Matos (2015), U.S. Geological Survey (2018). According to historical global statistics from the U.S. Geological Survey (USGS) Matos (2015), U.S. Geological Survey (2018), the leading iron-ore producers from 1900 to 2015 were China (38%), Australia (19%), and Brazil (17%). This high production of iron ore implies a loss of natural minerals in these countries Calvo et al. (2015), Valero and Valero (2014), Gabriel Carmona et al. (2015).

Additionally, a decarbonized society implies the use of renewable-energy technologies Sawyer et al. (2016), International Energy Agency (2010), World Steel Association (2017). These technologies require a considerable amount of metals, and steel is extensively needed; however, iron production is only economically feasible when ores with high concentrations of iron are available.

Because minerals are essential in modern society and rich mines are increasingly being depleted, the assessment of mineral resources is necessary. This can be done via three approaches: evaluation based on the mass, market prices, and the physical quality of the minerals. The first approach disregards essential aspects, such as the scarcity of the minerals in Earth’s crust Valero and Valero (2014), Domínguez and Valero (2013), Palacios et al. (2018). For instance, in this approach, one ton of iron is considered equal to one ton of gold, even though iron is more abundant than gold and the energy required to extract the metal from the ore (embodied energy) is higher for gold than for iron.

Regarding the second approach, metal prices are influenced by many factors and are thus volatile Henckens et al. (2016). One of

* Corresponding author.
E-mail addresses: jose.palacios@epn.edu.ec (J.-L. Palacios), i.belo-fernandes@hzdr.de (I. Fernandes), a.abadias@hzdr.de (A. Abadias), aliciavd@unizar.es (A. Valero), valero@unizar.es (A. Valero), m.reuter@hzdr.de (M.A. Reuter).

https://doi.org/10.1016/j.egyr.2019.03.004
2352-4847/

these factors is the difficulty of extracting metals from ores (cost of extraction) Valero and Valero (2014), Henckens et al. (2016). Another factor is speculation related to the physical reality of the commodities. According to historical data regarding commodity prices from the USGS Kelly and Matos (2016), the price of iron ore was lowest in 1901 (1.71 US$/t) and highest in 2012 with (116.48 US$/t). This shows the variability in iron-ore prices.

The third approach for the assessment of mineral resources involves the Second Law of Thermodynamics. Valero and Valero established the concept of the exergy replacement cost (ERC) for the evaluation of mineral resources Valero and Valero (2014), Valero et al. (2013). The ERC represents the energy needed to concentrate minerals at an average ore grade from Thanatia, which is an ideal illustration of mineral dispersion in Earth's crust Valero and Valero (2014). Thanatia symbolizes the common rock from which minerals would be concentrated. This idea is aligned with the research of Henckens et al. Henckens et al. (2016), who mentioned that the maximum cost of extraction of commodities would be set up as their mining would come from low-concentration deposits, common rocks, and seawater Henckens et al. (2016). Skinner reported that extraction from common rocks is technically feasible but requires more energy than extraction from rich metal ores Skinner (1976). Investigations by Harmsen et al. Harmsen et al. (2013), Bardi Bardi (2014), and Norgate and Jahanshahi Norgate and Jahanshahi (2010) reinforced the position of Skinner regarding the increment of the specific energy for the extraction of metals from low-concentration deposits. In research by Steen and Borg Steen and Borg (2002) on the direct costs of production of metals from Earth's crust through sustainable methods, considerable increments for metal concentrates, such as copper, cadmium, and manganese, were reported.

ERC values have been calculated according to an analysis of statistical trends, good estimations, or mathematical models. In this study, we estimate the specific energy needed to concentrate minerals from Thanatia via a more rigorous approach than the one used previously. The methodology developed for this endeavor relies on a computational model using the HSC Chemistry software Garcia et al. (2018), which is a specialized software for mining and metallurgical processes that is commonly used in industry. The aim is to provide accurate values regarding the amount of energy needed if no more concentrated iron-ore deposits exist. This exercise, which has not been previously performed with such detail, reveals the tremendous amount of energy savings due to having minerals concentrated in mines and not dispersed throughout the crust. Our study provides valuable insight regarding the sustainable production of metals, considering the loss of minerals experienced by modern nations. All of the aforementioned researchers based their methodologies on good estimations and assumptions, rather than rigorous metallurgical analysis of the energy needed in each process.

2. ERC and Thanatia

The ERC allows the quantitative evaluation of minerals. Exergy is a thermodynamic property of a system–environment combination that represents the minimum amount of work that a system can produce when it is brought into equilibrium with its surrounding environment Valero and Valero (2014), Cengel and Boles (2008), Bejan et al. (1996), Moran et al. (2011). When fossil fuels are burned, their liberation of energy is associated with their high heating value (HHV) Valero and Valero (2012a,b). Conversely, non-fuel minerals are noncombustible; thus, the association of the HHV and exergy is not valid. A common approach for assessing non-fuel minerals employs their chemical exergy. In an influential paper, Szargut published the chemical exergy of different elements Szargut (1989). The chemical exergy of elements has been used by other authors, such as Ayres Ayres (2016), Dewulf et al. Dewulf and Van Langenhove (2006), and Szargut et al. Calvo et al. (2015), Szargut et al. (2015, 2002), to evaluate mineral resources.

Nevertheless, chemical exergy is not effective for accurately assessing non-fuel minerals, as stated by Domínguez et al. Domínguez and Valero (2013). The chemical exergy of gold is 60 kJ/mol, and that of aluminum is 796 kJ/mol. Gold is scarcer than aluminum, and its chemical exergy does not adequately reflect this. Exergoecology was postulated by Valero Valero and Valero (2010) for the proper evaluation of mineral resources. Physical geonomics – one division of exergoecology – considers the application of exergy in the assessment of non-fuel minerals. The exergy of non-fuel minerals has two components; the first one is related to their chemical composition (chemical exergy), and the second one is associated with their relative concentration in Earth's crust (concentration exergy). The assessment with both components is more accurate than that the chemical exergy.

Nature provides a "free bonus", as minerals are concentrated in deposits rather than dispersed throughout Earth's crust. This "free bonus" significantly reduces the costs associated with the mining and concentration of mineral commodities. This free concentration of minerals can be seen as an "avoided cost" with regard to mineral processing and refining. When high-ore-grade mines are depleted, as is currently happening Calvo et al. (2016), there is a reduction in this free bonus. This leads to extensive exergy consumption for extracting a similar quantity of metal from a lower-ore-grade mine. The ERC is thus a measure of the "free bonus" provided by nature and quantitatively determines the loss of minerals for nations Calvo et al. (2015), Palacios et al. (2018), Valero et al. (2015).

The ERC is interpreted as the energy needed to extract and concentrate a mineral from a completely dispersed state (x_c) to the conditions of concentration and composition found in a mine (x_m) using available technology. Thanatia comes from the Greek word "Thánatos", which means death, and is an idealization of a "commercial death planet" in which all minerals have been mined and dispersed into the crust, and all fossil fuels have been burned Palacios et al. (2018), Valero et al. (2017). It is the baseline for calculating the concentration exergy of a mineral resource. The concept of Thanatia was developed by Valero and Valero Valero and Valero (2014) and represents a state of total mineral dispersion into Earth's crust (x_c). It is made up of 324 species, 292 minerals, and 32 diadochic elements Valero and Valero (2014), Valero et al. (2011). In our model for the concentration of high-iron-content minerals, we use Thanatia as a common rock. Because Thanatia has many minerals, only those with an iron content of >15% (by weight) are shown in Fig. 1. A complete list of the substances in Thanatia considered in the present study, along with their chemical formulas and percentages by weight, can be found in Valero and Valero (2014, p. 304). Owing to the high iron content of magnetite in Thanatia and because hematic deposits are highly valued for iron production, e.g., Carajás in Brazil. Hematite and magnetite are considered for concentration in our computational model.

The ERCs of different minerals were computed by Valero et al. Valero et al. (2013) by examining the behavior of ore decline and the energy consumption required for the concentration of cobalt, copper, gold, nickel, and uranium. Analysis of these data revealed that as the ore grade decreases, the energy for concentration increases exponentially Valero et al. (2013). Valero et al. proposed a general equation for estimating the energy consumption according to the ore grade:

$$E_{(X_m)} = A \cdot X_m^{-0.5}, \quad (1)$$

Table 1
ERC for iron ore in GJ per ton of the element (adapted from Calvo et al. (2017)).

Mineral	Mineral ore	x_c(g/g)	x_m(g/g)	ERC (GJ/t)
Iron ore	Hematite	9.66E−04	7.30E−01	18

where $E_{(X_m)}$ is the energy for the concentration and extraction of minerals at the ore grade (x_m), and the coefficient A is determined for each mineral. In the methodology of Valero et al., the ERC of each element is calculated under the assumption that the element is obtained from a single type of ore (usually the most common one). Hence, for the case of iron, the ERC was obtained under the assumption that iron is only obtained from hematite ores, which have a crustal concentration of 9.66 E-04 g/g, as shown in Table 1. A complete and updated list of the exergy required for concentrating minerals from Thanatia (x_c) to the average concentration (x_m) for different minerals based on the methodology of Valero et al. was presented by Calvo et al. Calvo et al. (2017).

Table 1 presents the ERC value of 73% hematite (Fe_2O_3) required for concentration from Thanatia (x_c) to the average concentration in mines (x_m).

3. Methodology

The purpose of this study is to develop a model for concentrating iron-bearing minerals, mainly magnetite and hematite, from Thanatia until a concentration in equivalent-iron content similar to the one published in the ERC for hematite (Fe_2O_3) is reached. This indicates a starting concentration of 3.6% iron in Thanatia (x_c) and an ending concentration of approximately 50% iron in the mine (x_m). The latter comes from the stoichiometric conversion of the iron content in 70% hematite reported for the ERC of hematite, as shown in Table 1.

The concentration of minerals involves the transportation of the rocks from the mine to the concentration plant and different processes of mineral concentration Rankin (2011). Thus, the total specific energy for concentrating iron ore at the average ore grade (∼50% iron) from Thanatia (3.63% iron) was considered as the sum of the energy for the ore-handling process and the energy for concentration. In our model, the minerals for concentration are obtained from Earth's crust; surface mining is assumed. As reported by Chapman and Roberts Chapman and Roberts (1983), ore transportation plays an important role in the total energy requirement of the ore-handling process. This is why the energy requirement for drilling and blasting is considered to be negligible in our model, in comparison with the energy for ore-handling and concentration. The ore-handling process involves the transportation of the ore from an open pit to the concentration plant, generally using haul trucks. At the facility, comminution and concentration are performed.

For the ore handling, a minimum distance between the mine and the facility was assumed, so that the fuel consumption per ton of ore prevailed over distance. Then, taking into account the iron concentration in the feed stream of 3.63 Fe%, the specific energy per ton of iron ore was calculated (see Fig. 2).

Because Thanatia is an ideal ore, the stages of comminution and concentration at the facility were designed according to an extensive literature review and analyses of different flowsheets of iron concentration plants. The fundamentals of iron-ore processing and the layouts of processing plants were adapted from Lu Lu (2015) and Sousa de Sousa et al. (2002). Technical reports of iron-ore projects were also studied Gignac et al. (2017), Tanghavel and Batista (2014), de Souza (2010), Sampaio et al. (2001). Publications by Houot Houot (1983) and Filippov Filippov et al. (2014) regarding the beneficiation of iron were reviewed, as well as papers regarding the flotation of iron ores by Frommer Frommer (1967) and Araujo et al. Araujo et al. (2005). The use of collectors and reagents for iron ores was examined according to the results of Schulz and Cooke Schulz and Cooke (1953), and a lifecycle assessment (LCA) of iron ore mining performed by Ferreira et al. Ferreira and Leite (2015) was considered.

The experience of the research group with regard to mineral processing was important for the final design of the model using the software HSC Chemistry version 9.5.1 Garcia et al. (2018). In the model, many variables were considered, but only the most important ones are described herein. For the simulation, an Intel core i7-6600 2.60 GHz central processing unit with 32 GB of random-access memory was used.

On the basis of the analysis of technical reports of iron projects Gignac et al. (2017), Tanghavel and Batista (2014), de Souza (2010), Sampaio et al. (2001), the study of the layouts in Lu (2015), and previous works on models by Abadías et al. Abadías Llamas et al. (2019), the ore feed for the model was assumed as 2,500 tons per hour with a top size of 600 mm. To illustrate the model, Fig. 3 depicts the main stages for the concentration of iron from Thanatia.

Three circuits in the comminution were considered for the model: crushing, grinding, and two regrinding stages for liberating the maximum amount of metal from Thanatia. The 80% passing through the primary crusher (F80) 264 mm is fed into the comminution circuit. Crushing is performed by a gyratory crusher and a cone crusher, with the particle-size output (P80) set as 200 and 60 mm, respectively. A screen with a cut size of 32 mm is placed in a closed circuit with the cone crusher. The screen reports to the grinding circuit, which consists of two ball mills. The sizes of the passing particles (P80) for these mills are 4000 and 75 μm, respectively. A cyclone between the ball mills with a cut particle size of 1000 μm is considered. The combination of the ball mill with the cyclone yields a particle size of approximately 75 μm.

A fundamental equation for computing the specific energy required for the mill during the comminution process is Bond's equation Wills and Napier-Munn (2006), Skarin and Tikhonov (2015):

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

where W is the specific energy consumption of the mill (kWh/t), W_i is the work index (Bond index) measured in a laboratory mill (kWh/t), and P80 and F80 are the 80% passing sizes of the product and the feed (−m), respectively. EF_x is the product of the Rowland efficiency factors, which depend on the mill, size, type of media, type of grinding circuit, etc. Wills and Napier-Munn (2006), Skarin and Tikhonov (2015), King (2001), Rowland (1982, 2002). The theoretical power draw by the mill (kW) is calculated as W × T, where T is the throughput tonnage (t/h) Wills and Napier-Munn (2006).

Eq. (2) was used to determine the theoretical power draw during the comminution stages. Both the feed (F80) and product (P80) passing sizes were obtained using the HSC model. The work index (W_i) for an unidentified iron ore can vary from 4 to 31 kWh/t Lindroos and Keranen (1985). For the first calculation of the specific energy consumption (W), a representative value of 14 kWh/t was considered. A similar value for this conversion (61.22 kJ/kg) was employed by Valero and Valero Valero and Valero (2012a) to calculate the exergy of comminution and concentration for different minerals.

To reduce the complexity of using the Rowland efficiency factors (EF_x) in Eq. (2), the procedure proposed by Will and Finch (Wills and Napier-Munn, 2006, Ch. 7) was followed for the selection of mills. Accordingly, a value of 1 for EF_x was

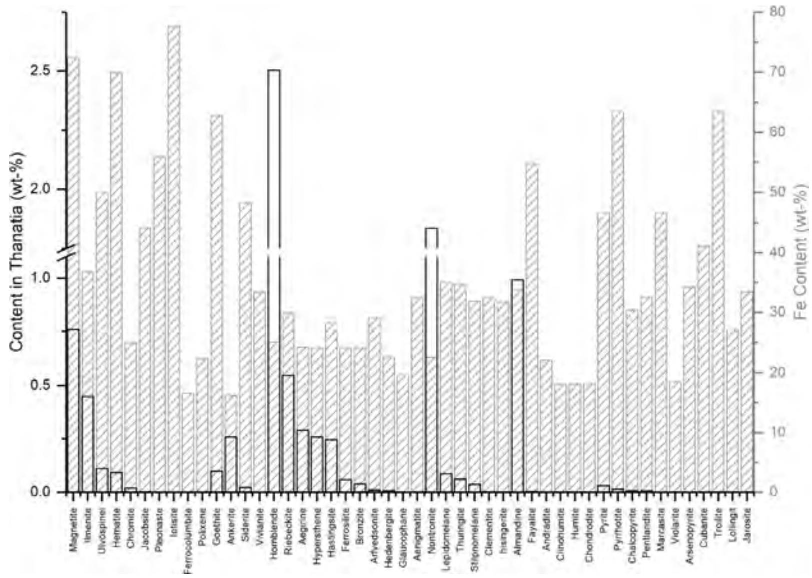


Fig. 1. Iron-bearing minerals in Thanatia. The left axis (in black) indicates the content of the minerals in Thanatia. The right axis (in gray) indicates the content of iron in the minerals.

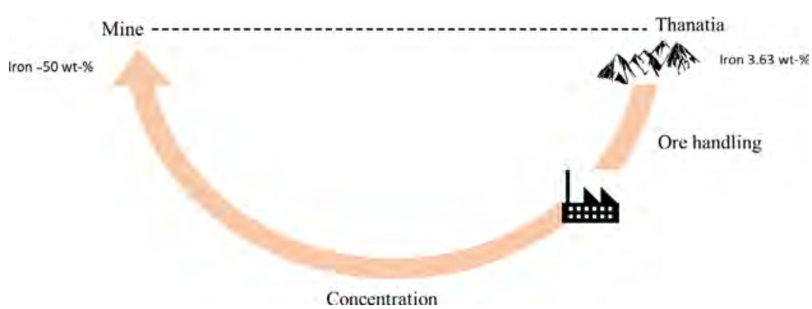


Fig. 2. Conceptualization of the total energy needed to concentrate iron ore from Thanatia as the sum of the energies for the handling and concentration processes.

assumed, and the specific energy consumption (*W*) for every mill was computed. According to the *W* values for the mills and information from catalogs provided by the manufacturers, models of mills were selected. Then, the number of mills was estimated. Data published in Metso (2010, 2008) for primary gyratory and cone crushers were considered. For the grinding and re-grinding ball mills, we considered a survey of data regarding the specific energy (7.82 kWh/t) for these tumbling mills reported by Latchireddi and Faria Latchireddi and Faria (2013). For classification, the power of spirals and low and high magnetic separators were taken from Metso (2015). The power required for the flotation process of the main iron-bearing minerals was obtained directly from the HSC model Garcia et al. (2018). The specific energy per ton of iron was determined according to the feed flow rate (2500 t/h) and the iron concentration in Thanatia (3.63% iron).

After the start of the classifying process in comminution, high-iron-content minerals are separated from the unwanted minerals because of their higher specific gravity (SG) and magnetic susceptibility. Thus, the comminution process reports to two spiral concentrators, where low-SG minerals, such as quartz and silicates, are partially separated. To ensure the separation of unwanted minerals, a combination of three classifying cyclones separates fine particles (low SG) from coarse ones (high SG). The overflow of the cyclones undergoes a low–high magnetic separation process to remove iron minerals with low and high densities. The high iron minerals are transferred to the final concentration stage.

On the other hand, the underflow of the cyclones reports to a combination of low and high magnetic separators to upgrade the iron content. Magnetite is removed from the low-magnetic intensity separators owing to the high magnetic susceptibility. From the circuits of the rougher, scavenger, and cleaner of high intensity and magnetic gradient separators (SLon), hematite is recovered. Both the magnetite and hematite retrieved from the magnetic separation circuits are employed in the reverse flotation process.

Before the reverse flotation process, regrinding in a ball mill to 40 μm is required. The flotation process consists of two stages: arrangements of rougher, scavenger, and cleaner cells and a re-cleaner stage. The feed to the first stage of reverse flotation is approximately 23% iron, which is a common iron content in concentration plants. The combination of the steps of reverse flotation, recirculation, cleaners, and re-cleaners assures that the iron content at the end of the flotation is 63.63%. Then, this stream is mixed with another stream coming from the classifying stage having a high magnetite content. For the flotation process, fast kinetics constants (kf) are set up following those reported by Saleh Saleh (2010). The volume and number of cells for the

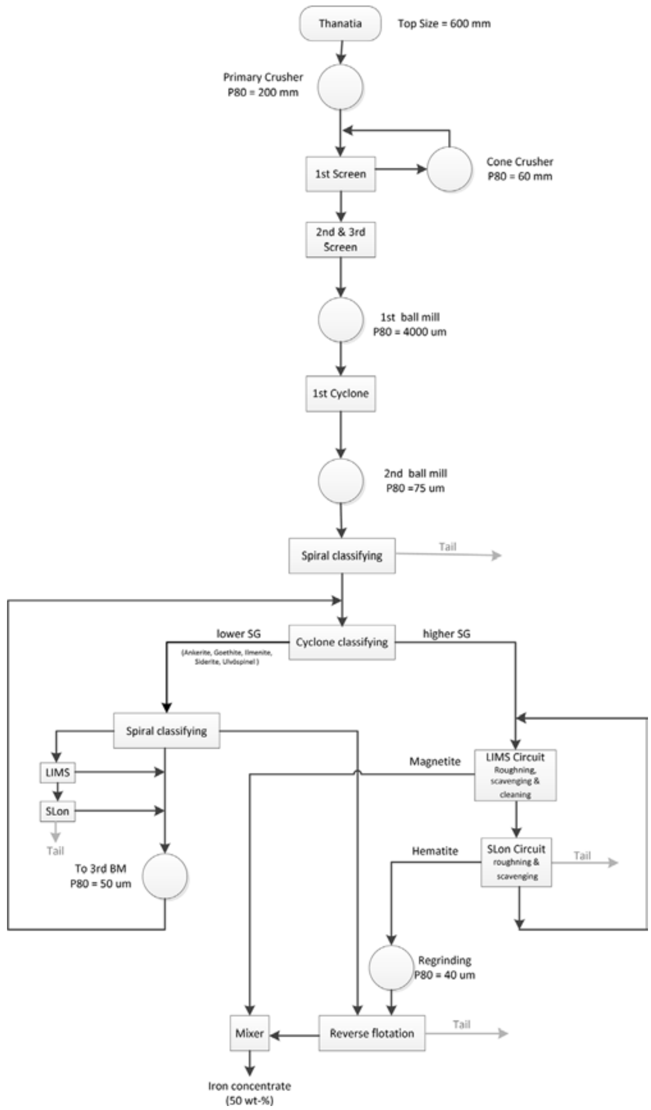


Fig. 3. Flowsheet of concentration and tailings from Thanatia to iron ore.

flotation tanks are established according to typical values of cells per bank from manufacturer data published by Weiss Lindroos and Keranen (1985) and Wills and Finch Wills and Napier-Munn (2006).

The arrangement of the equipment for the comminution and concentration processes described above is shown in Appendix.

4. Results and analysis

In this section, the results of the simulation are presented. The results are validated through a comparison of the key parameters of the comminution and concentration process with those in the literature. Finally, according to the methodology, the calculation of the specific energy through a sensitivity analysis is presented.

4.1. Simulation results

For the developed model, the direct results were the particle size for the feed (F80) and output (P80) of the crushers and mills in the comminution process, as shown in Table 2. The reduction ratio (Rr) is the particle size of F80 divided by that of P80. The total reduction ratio is the product of every mill, as indicated in Metso (2015). For the flotation process, the direct results were the retention time and power consumption, as shown in Table 3.

The result of the flotation process was a product with a mass flow rate of 19.72 t/h and an iron content of 58.10%. The main minerals in the concentrate are shown in Fig. 4. Owing to the large number of iron-bearing minerals in Thanatia, as shown in Fig. 1, recovered product mainly compromised high-iron-content minerals (mainly magnetite and hematite). This is why the recovery of iron was only 12.62% in our model. On the other hand, the recovery of hematite and magnetite was 25.13% and 79.06%, respectively.

Table 2
Feed (F80), product size (P80), reduction ratio, and specific energy (W) for every mill for the comminution process.

Stage	Equipment	F80 (−m)	P80 (−m)	Reduction ratio (Rr)
Crushing	Primary crusher	245631	200000	1
	Secondary crusher	215737	60000	4
Grinding	1st ball mill	11695	2400	5
	2nd ball mill	796	75	11
Re-grinding	3rd ball mill	60	50	1
	4th ball mill	66	40	2
Total				436

Table 3
Retention time and power draw for the flotation process.

Stage	Retention time (min)	Power (kW)
Rougher (RG)	28	90
Scavenger (SCV)	17	44
Cleaner (CL)	26	74
Scavenger 1	36	44
Cleaner 1	8	22
Cleaner 2	7	22

Table 4
The total specific energy of the comminution process according to the HSC model and the literature.

Stage	Equipment	Source	Specific energy (kWh/t)
Crushing	Primary crusher	Metso (2010)	0.27
	Secondary crusher	Metso (2008)	0.57
Grinding	SAG mill	Latchireddi and Faria (2013)	10.26
	Ball mill	Latchireddi and Faria (2013)	16.27
Re-grinding	HIG mill	Wills and Napier-Munn (2006)	18.72
TOTAL			27.36
Crushing and grinding iron ore		Bleiwas (2011)	20–30

4.2. Validation of model

To validate the HSC model, key values obtained using the model were compared with corresponding values in the literature. An important parameter for the comparison was the total specific energy of the comminution process. The selection of the models and capacities of every mill was performed as explained in Section 1. This procedure involves the use of information provided by the developed HSC model and catalogs from manufacturers. Under these assumptions, Table 4 shows the total specific energy of the comminution process.

The total specific energy based on the HSC model shown in Table 4 has the same order of magnitude as the values published by Bleiwas Bleiwas (2011) (for the electricity used in the crushing and grinding for the production of iron and steel in sub-Saharan Africa).

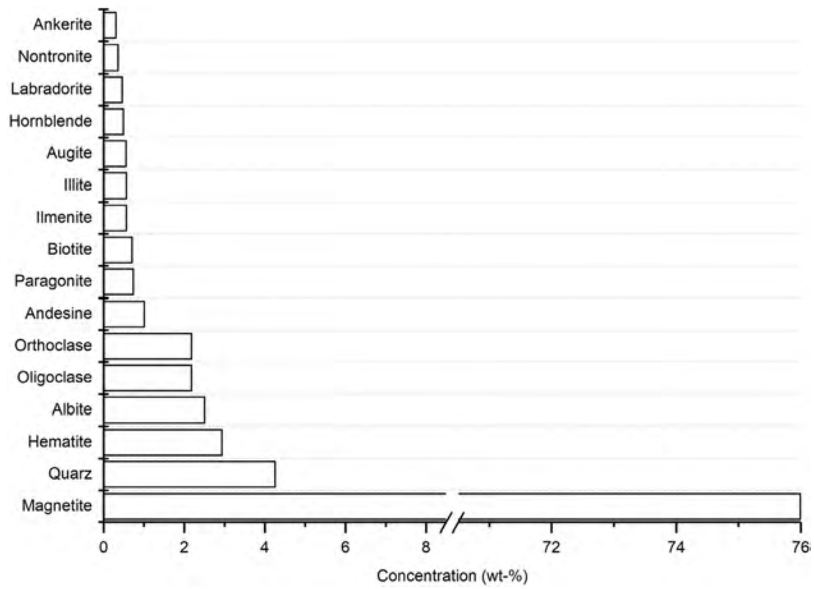


Fig. 4. Minerals in the concentrate at the end of the reverse flotation.

Table 5
Power draw for the comminution and concentration processes.

Stage	Power demand (MW)	Power demand (%)
Crushing	2	1.9
Grinding	71	87.1
Re-grinding	9	10.6
Classifying	0.06	0.1
Reverse flotation	0.52	0.4
TOTAL	81	

Table 6
Specific energy for the concentration of iron minerals from Thanatia in kWh per ton of ore.

	Iron concentration (wt-%)	Flow rate (t/h)	Specific energy (kWh/t)
Feed ore	3.63	2500	33

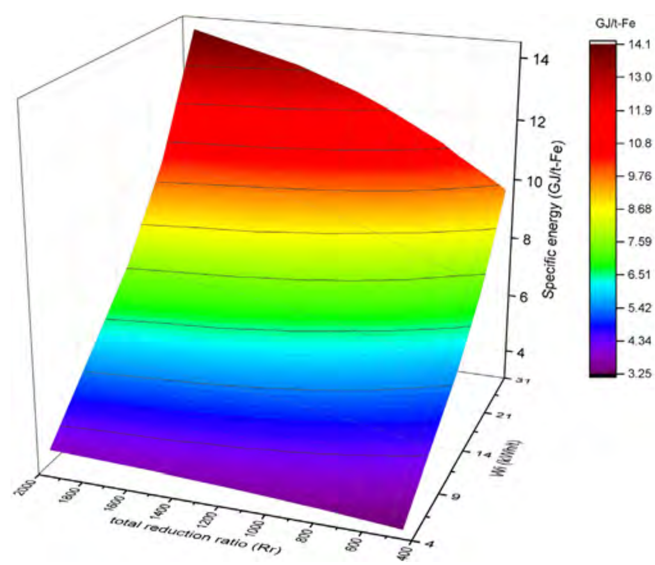


Fig. 5. Specific energy for the concentration of high-iron-content minerals from Thanatia with respect to the total reduction ratio (Rr) and Bond work index (W_i)

The retention time for the HSC model, as shown in Table 3, is in the expected range of values reported by Lu (2015), Lindroos and Keranen (1985), Fuerstenau et al. (2007). For the rougher, cleaner, and scavenger 1, retention times of >30 min were obtained owing to the need for recirculation in the flotation circuits.

Considering the complexity of Thanatia as a mixture of low-content minerals and the uniqueness of the flowsheet developed in the present study, the results of the HSC model are logical and reliable.

4.3. Specific energy for iron concentration

As indicated by Eq. (2), the specific energy consumption W of the mill necessary to calculate the power demand is based on the work index (W_i). In a first attempt to determine the specific energy, a value of 14 kWh/t was considered, as mentioned in Section 3. With these considerations and others previously explained for the model setup, the power demand for the flotation plant was estimated, as shown in Table 5.

As shown in Table 5, most of the power demand was due to the comminution process (>99%), with grinding accounting for the largest power consumption. Using the methodology described in Section 2, we calculated the specific energy for the concentration of high-iron-content minerals from Thanatia, as shown in Table 6.

To estimate the specific energy required for ore handling, consumption of 2.2 kg/t was considered, as reported by Norgate and Haque Norgate and Haque (2010) in their work based on LCA for iron ore and other minerals. The specific energies for the ore handling, which involves the transportation of ore from the mine to the concentration plant, and concentration, including the stages of crushing, grinding, re-grinding, and reverse flotation, for a W_i of 14 kWh/t are shown in Table 7.

Table 7
Specific energy for the concentration of iron-ore from Thanatia in GJ per ton of the element.

	Specific energy (GJ/t-Fe)
Ore handling	2.3
Concentration	3.2
TOTAL	5.6

Table 8
Total reduction ratios of the mills for the sensitivity analysis.

Scenario	Total reduction ratio (Rr)
1st	436
2nd	491
3rd	574
4th	657
5th	739
6th	844
7th	958
8th	1145
9th	1433
10th	1943

4.4. Sensitivity analysis

Because Thanatia represents a complex ore, its Bond index W_i cannot be accurately determined for a large number of minerals. Thus, it is appropriate to estimate the specific energy through a sensitivity analysis. This analysis is based on the variation of W_i from 4 to 31 kWh/t – a possible range for iron ores – as described in Section 1. The values considered for the sensitivity analysis were: 4, 9, 14, 21, and 31 kWh/t. According to the developed HSC model and the methodology described in this work, the specific energy required for concentrating iron minerals from Thanatia is accurately represented by the variation of the parameters of the comminution process, the highest energy consumption stage, and the hardness of the rock. These parameters are represented by the total reduction ratio (Rr) and the Bond work index (W_i). In essence, the sensitivity should be taken as the uncertainty of the required final particle size needed to liberate the iron metal from unwanted minerals and the hardness values of the rock. Table 8 shows the range of total reduction ratios considered for the sensitivity analysis.

Similarly, as reported in Table 7, Fig. 5 shows the specific energy for the concentration of minerals with high content of iron from Thanatia. In the analysis, the total reduction ratio (Rr) was changed, as shown in Table 2, to represent the different particle sizes required for extracting iron from the minerals in Thanatia.

The results for the specific energy in Fig. 5 were obtained under the assumptions made in Section 3, with the layout of mills, classifiers, magnetic separators, flotation cells, and recirculation circuits shown in Appendix.

As shown in Fig. 5, the specific energy increases as the total reduction ratio (Rr) increases. There is a proportional relationship between the specific energy and the Bond work index, as indicated by Eq. (2).

The result based on the HSC model is compared with the ERC value converted into iron content (through molecular weights) and the embodied energy (mining and concentration) of iron reported by Calvo et al. Calvo et al. (2017). The energy spent on loading and crushing reported in Norgate and Haque (2010) is used to draw a comparison. In the model, the values of the specific energy can vary according to Rr and W_i. For the lowest Rr (436) and softest rock ($W_i = 4$ kWh/t), the energy required was 3.3 GJ/t-Fe. For the highest Rr (1943) and hardest rock (W_i = 4–31 kWh/t), the energy required was 14.1 GJ/t-Fe.

Table 9
Comparison of the specific energy (in GJ per ton of element) between the present work and other reported values.

	Specific Energy (GJ/t-iron)	Source
ERC based on HSC	3.3–14.1	Present work
Previous ERC	18	Calvo et al. (2017)

Table 9 summarizes the results and compares them with previously reported values, under the assumptions explained in Section 3.

The previous ERC has the same order of magnitude of the specific energy as the present work with a combination of the finest particles (Rr = 1943) and the hardest iron ore (Wi = 31 kWh/t). Importantly, in our model, minerals with a high iron content were concentrated. The mathematical calculation of the ERC for iron by Valero et al. corresponds to only hematite, as shown in Table 1.

As shown in Fig. 5, **t**he specific energy for the concentration of iron minerals depends on the hardness of the rock (W_i) and the final particle size (represented by Rr). As shown in Table 7, for $W_i = 14$ kWh/t, which was also considered by Valero and Valero Valero and Valero (2012a) as a common value for different minerals, and a common final size of P80 = 40 μm (Rr = 436) for iron ore, the specific energy for the concentration is 5.6 GJ/t-Fe. This value can be considered as a "New ERC for iron from HSC", assuming that Thanatia exhibits behavior similar to that previously described ($W_i = 14$ kWh/t and Rr = 436).

In summary, the previous and new ERCs for iron differ considerably in the method of estimation. While the previous one was determined only according to mathematical and analytical analysis, the new one has strong support from a metallurgical viewpoint. For the previous ERC for iron, it was roughly assumed that only hematite could be concentrated from Thanatia. On the other hand, from a more realistic perspective, minerals with a high iron content in Thanatia, such as magnetite and hematite, are easily concentrated, and their separation is difficult. Additionally, in the case of the previous ERC, the processing of iron to obtain pellets or lumps for producing pig iron implies an additional expenditure of energy. This is because in the calculation of the previous ERC, the separation process (crushing and grinding) was not even considered. In contrast, further treatment for the iron ore of the new ERC allows energy saving because the ore is already ground to P80 = 40 μm.

5. Conclusions

This study was the first attempt to rigorously assess the hypothetical energy needed to extract minerals from common bare rock. The assessment is fundamental for understanding the mineral capital of nations and the implications of the depletion of high-grade mines for future generations. Nature provides minerals concentrated in mines rather than dispersed throughout the crust, which saves a large amount of energy. However, as minerals become depleted, this free natural bonus decreases, and energy expenditures increase. In the ultimate limit, the calculated energy costs are not hypothetical but real. Accordingly, assessing the "free energy bonus" allows the mineral patrimony of nations to be measured in a physical manner.

Theoretical and academic analyses to assess this bonus were previously performed for various minerals. These analyses involved assumptions and extrapolations that may be valid for determining the orders of magnitude but are not accurate enough. With the help of HSC software and the team at Helmholtz Institute Freiberg for Resource Technology (HIF), we for the first time simulated a real mining and the metallurgical process starting with Thanatia, and hence obtained accurate values for iron production.

The computational model was developed by studying different layouts of iron-ore concentration plants and leveraging the experience of the members of the research team at HIF and the Research Centre for Energy Resources and Consumption (CIRCE Institute).

To validate our results, we compared the parameters obtained from the model with others obtained from a literature review. Furthermore, we performed a sensitivity analysis by changing two key parameters for the concentration of iron minerals. The first parameter characterizes the uncertainty of the final particle size before the reverse flotation processes, because of the requirement to liberate iron metal present in a very low concentration in Thanatia. This is represented by the variation of the particle size in the comminution process (Rr). The second parameter in the sensitivity analysis denotes the variation of hardness in Thanatia according to the Bond index. From the model, a "New ERC for iron" of 5.6 GJ/t-Fe can be obtained by assuming that Thanatia exhibits behavior similar to that previously described (W_i = 14 kWh/t and Rr = 436). This value is three times lower than the previous one (18 GJ/t). The values differ with regard to the method of calculation. While the previous value was estimated via mathematical and analytical analysis, the new one has strong support from an engineering viewpoint, as it was obtained using the specialized software HSC Chemistry.

In future research, additional models will be developed for other minerals to compare and update the previously obtained ERC values.

The results of this study highlight the need to value high-iron-content deposits, particularly in countries where the iron ore is vastly extracted. Although steel is the most extensively recycled metal, its consumption is expected to increase significantly in the coming years with the need for renewable-energy technologies. Thus, sustainable methods for the production of metals that satisfy the needs of the present and future generations are necessary. Additionally, the loss of natural patrimony in nations where minerals are extracted should be taken into account. The roles of these nations in a globalized economy should be reconsidered.

Acknowledgments

We thank the National Secretary of Science and Education of Ecuador (SENESCYT) for the support to publish this paper in an open-access version. This study received funding from the Spanish Ministry of Economy and Competitiveness under the framework of project ENE2017-85224R. We thank Prof. Dr. Oscar Restrepo of Universidad Nacional de Colombia for providing a valuable bibliography, Frans Van Schalkwyk of the Helmholtz Institute Freiberg for Resource Technology for the revision of the computational model, and three anonymous reviewers whose comments greatly improved the quality of the paper.

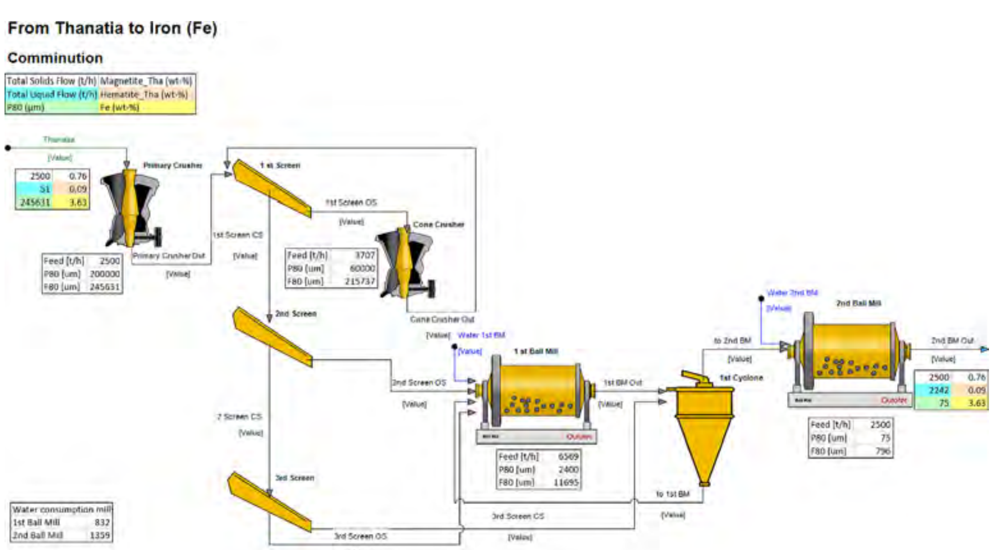
Author contributions

Palacios, J.L performed the literature review, model construction, and simulations and wrote the first parts of the paper. Fernandes, I. and Abadias, A. supported the modeling and simulation. Valero, An. and Valero, Al. supervised the research on the calculation of the energy consumption for upgrading the ERC for copper. Reuter, M. provided metallurgical advice and supervised the modeling and results.

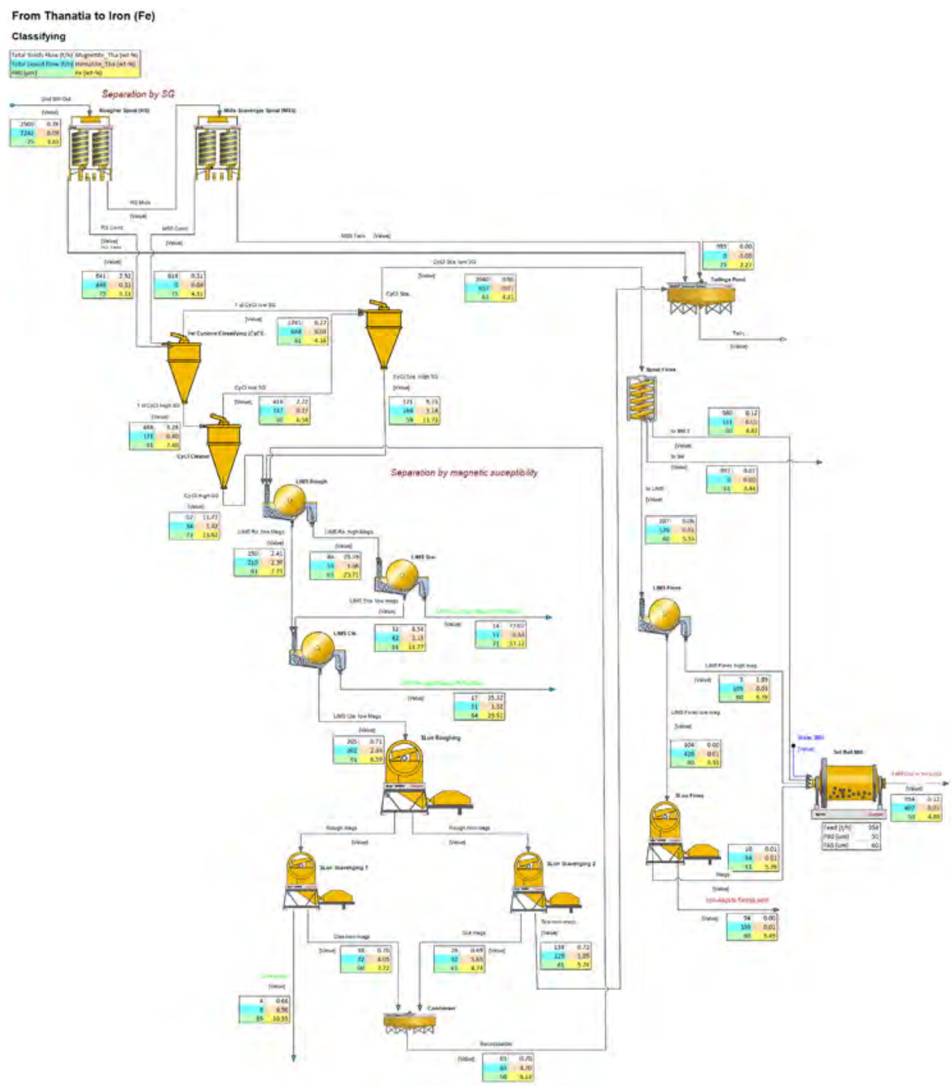
Conflict of interest

The authors declare no conflicts of interest

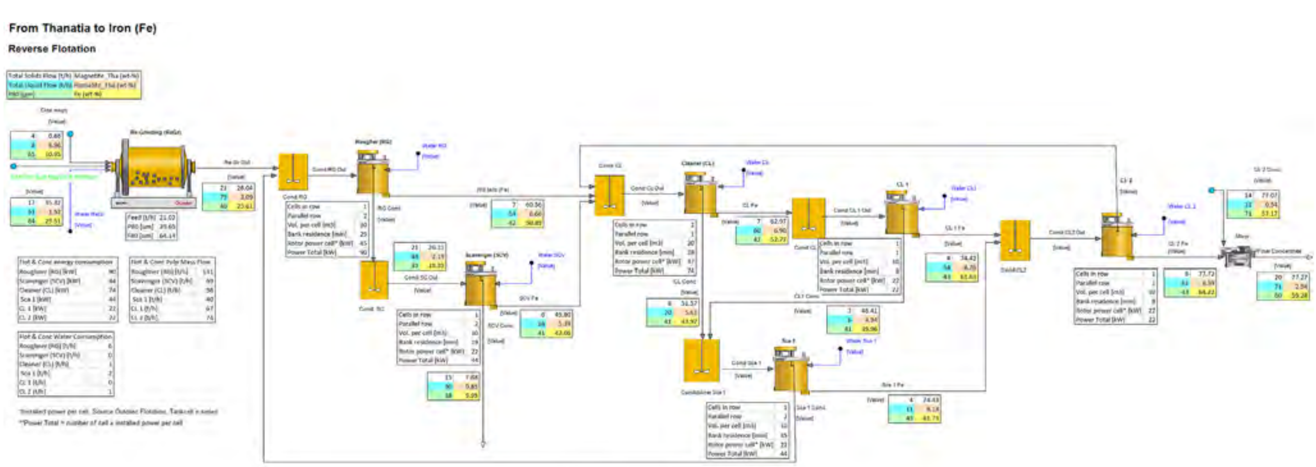
Appendix



Comminution stage



Classifying stage



Reverse flotation stage

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