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Assessing the role of renewable energy in mitigating the impacts of declining ore grades in mining

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A B S T R A C T

Energy stands as one of the main constraints for the mining sector, with a focus on transitioning to green energy. Different scenarios have been created to evaluate the impact of integrating renewable energies into the mining industry. This analysis, based on exergy and projected until 2050, shows a significant increase in the final exergy costs. However, when the exergy cost is decoupled into primary energy, a notable reduction in non-renewable exergy is observed with the incorporation of renewable energies, preserving natural resources such as oil, coal, and natural gas. Additionally, it has been observed that the anticipated ore grade decline from 2050 of 75 % for Pb, 81 % for Zn, 55 % for Au, 82 % for Ni, and 87 % for Ag could be compensated in terms of non-renewable exergy costs if renewable electricity is fully integrated into the mining industry.

1. Introduction

Energy has become one of the main constraints in mining and metal production, not only because of the important cost operation (around 38 % of the total cost), but also for the significant amount of energy currently used and expected in the future, and due to its substantial greenhouse gas emissions (Aramendia et al., 2023). It is a fact that this industry still relies primarily on fossil fuels, consuming about 19 % of coal and coal products, 5 % of global gas, and 2 % of global oil supplies (Igogo et al., 2021).

There is a growing consensus to make the mining industry more environmentally sustainable. This includes a shift towards integrating renewable energy sources into mining operations (Chen et al., 2023; Littleboy et al., 2019). Therefore, renewable energy technologies, such as solar, wind, and hydroelectric power, provide an alternative to fossil fuels, potentially reducing the carbon footprint. However, this transition will proceed slowly, with the goal of achieving net-zero emissions by 2050 (Dou et al., 2023). By decoupling the current energy sources used in the mining industry from the availability of newly introduced renewable energy sources, it is possible to assess the feasibility of this transition and determine the energy requirements for extracting specific metals.

Similar studies have been carried out related to this concern, assessing the amount and type of energy required to extract some metals. For instance, in the work conducted by (Torrubia et al., 2023a), the energy footprint for several metals was analyzed, dividing this energy into four types of fuels: natural gas, diesel, coal, and electricity. The energy was further decoupled into different processes of beneficiation, including comminution and concentration, smelting and refining, and the energy associated with the production of chemicals. On the other hand (Ulrich et al., 2022), carried out a study to analyze the transition from fossil fuels to renewable energy sources. They used the case of gold, evaluating the energy transition by comparing the greenhouse gas emissions intensity when applying non-renewable sources versus renewable sources. Van der Voet et al. (2019) developed in their work a methodology to quantify environmental impacts. For this purpose, six major metals were evaluated based on the cumulative energy demand for each of them and the greenhouse gas emissions, projected to the year 2050. However, although energy mixes and ore grade decline were mentioned, primary energy was neither assessed nor included in their projections. Magdalena (2024) and Calvo (2016) in their respective works assessed the energy requirement for metals when the ore grade declined. Magdalena et al. (2023) carried out this analysis with a specialize software called HSC Chemistry, calculating the energy consumption of the units involved in the beneficiation process for different ore grades. Calvo et al. (2016), based on real data from mines and concentrations, calculated a trend in the energy requirement for metal extraction as a function of ore grade. In the work conducted by Hu et al. (2024) it was highlighted the criticality of ore grade decline and its impact on the material energy nexus. A more extensive study was carried out by Elshkaki and Shen (2019), where they analyzed the energy nexus under different energy scenarios. However, their study was

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assessed according to the cumulative production of several metals and the cumulative installed power of renewable energy sources until 2050.

While numerous studies have analyzed the energy consumption and environmental impacts of the mining industry, they have not decoupled energy use to assess these effects. For instance, Aramendia et al. (2023) focused their work on the estimation of the global final energy consumption of the mining industry, investigate future pathways for the industry's final energy consumption in 2060, and the energy requirements of materials flows according to the pathways they selected. Li et al. (2024) assessed in their work the implications for the transition to Renewable Energy practices in the mining industry. However, this study is not carried out quantitatively, but rather assessing perspectives to be considered for the feasibility of this transition. Last, Song et al. (2025) investigated sustainable mining practices to reduce the environmental footprint, as well as promoting the responsible resource extraction. Thus, decoupling the energy in mining industry remains as a challenge. Accordingly, this paper addresses that gap by evaluating impacts based on the energy required for metal recovery. Therefore, it provides a reference for examining the benefits and savings of non-renewable resources through the integration of renewable energy in primary production.

Accordingly, the impact on natural resources during the transition to renewable energies will be calculated by determining the exergy costs for six different metals, including copper, lead, zinc, gold, nickel, and silver, considering ore grade decline. Additionally, this exergy cost will be decoupled into different sources, renewable and non-renewable, over time (until the year 2050), and specifically calculated for the individual metals mentioned. With this assessment, the aim is to analyze the transition from fossil fuels to renewable energies in the mining industry, considering not only the expected yearly integration until 2050 but also the types of sources suitable for these transitions. Finally, given the uncertain future of renewable energy capacity in the mining sector, the study will explore multiple scenarios to encompass a broad range of potential developments and outcomes.

2. Data and methodology

In this paper, the final exergy cost is used as an indicator to evaluate the primary energy consumption in metal production. This metric has been chosen over Life Cycle Assessment (LCA) due to its advantages in assessing resource efficiency as well as because exergy loss is linked to irreversibilities in the system. While LCA focuses on calculating and evaluating the environmental impacts of metal extraction and industrial use, it does not quantify the losses generated during the process. In contrast, exergy cost relies on the exergy parameter, which accounts for the physical quality of resources and quantifies the useful work potential of a system as it moves toward equilibrium with the environment. Exergy cost represents the total amount of high-quality exergy required to extract and process a natural resource into a useable product (Szargut et al., 1988; Valero et al., 1986). By using this approach, a direct connection between material consumption and energy demand is established (Torrubia et al., 2024).

Accordingly, this section explains the calculation of the final exergy cost disaggregated into several categories depending on the origin of the exergy source. Secondly, we selected six metals whose ore grade shows a consolidated declining trend over time. Then, we explain the calculation of the evolution of the final exergy cost according to the declining ore grades. Finally, we convert the final exergy into primary exergy to assess the consumption of primary resources in metal production.

It must be noted that the data collection for this article comes from different sources and situations. While some of them have been obtained from references based on simulations, other empirical data from mines has been found (e.g. gold ore grade from Australian mines). This will be explained along the paper.

2.1. Final exergy cost

The energy requirements for metal extraction and processing vary depending on ore composition and refining methods. Cu and Zn rely on flotation for concentration, but while Cu refining involves energy-intensive electrowinning or pyrometallurgy, Zn is refined through electrolysis, making electricity a key factor for both (Moore, 1990; Sinclair, 2005). Pb and Ag, often extracted together, undergo flotation followed by smelting, with Pb requiring significant thermal energy and Ag commonly recovered as a byproduct (Sinclair, 2010). Au and Ni show greater variability. Au extraction depends on cyanidation or gravity separation, with high milling and chemical use, while Ni processing varies by ore type, with laterites requiring energy-intensive acid leaching and sulfides processed through flotation and smelting (Crundwell et al., 2011).

The exergy cost varies significantly among metals, reflecting differences in extraction methods, refining processes, and energy inputs required at each stage of production. The final exergy cost of metals (b^*_{M-F}) represents the total exergy destroyed in producing a metal, from extraction at the mine to its final use, i.e., from "cradle to gate." In other words, the final exergy cost of a metal or material includes the final exergy of the metal itself plus the sum of all irreversibilities (i.e. destruction of resources) generated throughout the production process. More specifically, it accounts for the exergy of all fuels and minerals consumed during production.

Fig. 1 illustrates the calculation scheme for the final exergy cost of metals, represented as b^*_{M-F} and measured in MJ/kg. This figure illustrates a general metal production system without co-production, including four production processes (referred to as stages or phases hereafter): "Mining & Concentration (MC)," its associated chemical production (MC-CP), "Smelting & Refining" (SR), and its associated chemical production (SR-CP). The MC-CP and SR-CP stages represent the energy requirements for producing chemical products later used in metal production.

This study considers up to 25 chemical products, including ammonia, hydrochloric acid, limestone, oxygen, phosphoric acid, quicklime, soda ash, and sulfuric acid. Additionally, the exergy cost is categorized according to its source, dividing it into mineral exergy ($b_{Mineral}$) associated to the chemical composition of the resource, and four fuel types (natural gas, oil, coal, and electricity), resulting in a total of 17 subdivisions. It is important to note that electricity is considered the final energy input in the exergy cost calculation, which is why this is referred to as the final exergy cost.

The *final exergy cost* of a metal is calculated through equation (1).

$$\begin{aligned} B_F^* = B_{Mineral} &+ B^*_{NG-M\&C-C} + B^*_{Oil-M\&C-C} + B^*_{Coal-M\&C-C} + B^*_{Elec-M\&C-C} \\ &+ B^*_{NG-M\&C(EFC)-C} + B^*_{Oil-M\&C(EFC)-C} + B^*_{Coal-M\&C(EFC)-C} + B^*_{Elec-M\&C(EFC)-C} \\ &+ B^*_{NG-S\&R} + B^*_{Oil-S\&R} + B^*_{Coal-S\&R} + B^*_{Elec-S\&R} + B^*_{NG-S\&R(EFC)} \\ &+ B^*_{Oil-S\&R(EFC)} + B^*_{Coal-S\&R(EFC)} + B^*_{Elec-S\&R(EFC)} \end{aligned} \tag{1}$$

$B_{Mineral}$ was obtained from the reference (Valero et al., 2018) and is constant over time and for any ore grade. We obtained disaggregated energy costs from the reference (Torrubia et al., 2023) and transformed into exergy through the conversion factors of (Torrubia, Valero et al., 2024; Valero and Valero, 2012). However, the exergy costs ($B^*_{Fuel-Step}$) of equation (1), are not constant over time. Fossil fuel costs ($B^*_{NG,Oil,Coal-Step}$) depend on the energy return on investment (EROI) of fossil fuels in a certain year and we obtained their evolution from (Hall et al., 2014; Torrubia, Valero, et al., 2024). Furthermore, the decline in ore grade impacts only the exergy costs of the M&C step ($B^*_{Fuel-M\&C}$), since a lower ore grade does not necessarily increase the energy consumption of the refining stages (Smelting & Refining). This is because a fixed-grade concentrate is produced in the concentrating stage, regardless of the initial ore grade (Norgate and Haque, 2010).

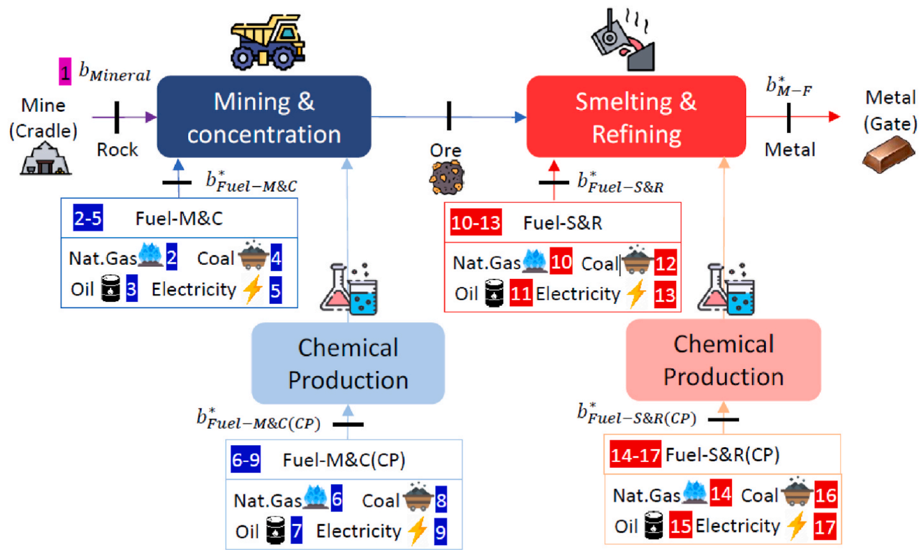

Fig. 1. Scheme of the calculation of the exergy cost.

2.2. Decline in ore grade

The decline in ore grades poses significant global challenges, driving higher energy demand and extraction costs in the mining sector. Processing lower-grade ores requires more energy and material input per unit of metal produced, leading to increased emissions and environmental impacts. This not only amplifies the footprint of renewable energy technologies but also raises the overall production cost, particularly under energy-intensive conditions. As demonstrated by Magdalena (2024), a decrease in the cut-off grade further intensifies these effects, as it expands the volume of material processed for the same metal yield. Because of this, estimating an economic cut-off is very complex and it is not possible to create a simple model. Consequently, unless offset by technological improvements or efficiency gains, market prices for metals are likely to rise in order to maintain economic viability, especially in scenarios of declining ore quality and increasing energy costs (Magdalena, 2024).

While this transition may raise operational costs in the short term, it could enhance long-term sustainability and resilience against fossil fuel price volatility. To accelerate this shift, policy measures are essential, including subsidies for green mining technologies, stricter emissions regulations, and incentives for recycling. It must be noted that this study does not consider potential technological advancements and consequently assumes that metal extraction costs will increase according to the cut-off of the mine.

However, not all metals experience a clear decline in ore grade over time. For example, Van der Voet et al. (2019) found that Fe or Al maintains a constant ore grade. For this reason, our study focuses on Cu, Ag, Au, Ni, Pb and Zn as all of them exhibit a decreasing ore grade consolidated over time. Fig. 2 shows the declining trend of ore grade for the metals mentioned above. The solid points in Fig. 2 show empirical data from mines collected by G. Mudd et al. (2013), G. M. Mudd (2007) and Northey et al. (2014). The decline is evident in all these metals. For example, in 1900 copper had an ore grade of approximately 3 %, while currently it is around 0.5 %. Following these tendencies, we extrapolate the empirical data up to 2050, following the methodology proposed by Van der Voet et al. (2019). Therefore, we can propose a rough estimate of the ore grade of each metal in 2050 (note that the according to the best of our knowledge, the data cited from the literature reflects the most current information found at the time of writing, with no updated values available).

2.3. Evolution of final exergy cost

The evolution of the mining and concentration exergy cost $B^*_{Fuel-M\&C}(x)$ is calculated with equation (2), from the current exergy cost ($B^*_{Fuel-M\&C-c}$), the current concentration in the mine (x_c), and the variation of the ore grade (x). We obtained x_c from (Van der Voet et al., 2019) and the variation of x is presented in Fig. 2 associated to a specific year.

$$B^*_{Fuel-M\&C}(x) = B^*_{Fuel-M\&C-c} \cdot \frac{x_c}{x^b} \tag{2}$$

The exponent b is an experimental parameter that indicates how fast the curve rises. Some authors (Calvo et al., 2016; Van der Voet et al., 2019) have estimated this parameter: copper (0.529), zinc (1), lead (1), nickel (0,406–0,494). If unknown, we estimate it at 1, which indicates that if the ore grade is halved, meaning that if the ore grade is halved, the energy required will double.

Fig. 3 shows an example of the evolution of the *final exergy cost* obtained. The mineral exergy ($B_{mineral}$) and the S&R exergy cost $B^*_{Fuel-S\&R}$ are constant and only M&C exergy cost ($B^*_{Fuel-M\&C}$) varies as a function of the ore grade (x) up to (x_T), which would represent the limit of extraction.

Considering the above, it is possible to calculate the evolution of the *final exergy cost* (B^*_{F-yr}), through equation (3) for a given ore grade and a given year.

$$\begin{aligned} B^*_{F-yr} = {} & B_{Mineral} + B^*_{NG-M\&C-yr} + B^*_{Oil-M\&C-yr} + B^*_{Coal-M\&C-yr} + B^*_{Elec-M\&C-yr} \\ & + B^*_{NG-M\&C(EFC)-yr} + B^*_{Oil-M\&C(EFC)-yr} + B^*_{Coal-M\&C(EFC)-yr} + B^*_{Elec-M\&C(EFC)-yr} \\ & + B^*_{NG-S\&R-yr} + B^*_{Oil-S\&R-yr} + B^*_{Coal-S\&R-yr} + B^*_{Elec-S\&R-yr} + B^*_{NG-S\&R(EFC)-yr} \\ & + B^*_{Oil-S\&R(EFC)-yr} + B^*_{Coal-S\&R(EFC)-yr} + B^*_{Elec-S\&R(EFC)-yr} \end{aligned} \tag{3}$$

However, the energy mix used in the extraction can vary in the future which affects the primary exergy cost (B^*_p) of the metals.

2.4. Evolution of primary exergy cost

As it has been already seen, the final exergy cost of each metal has been divided into 17 categories, combining four production stages, four fuels, and the chemical exergy of the ore. The exergy cost of the ore and fossil fuels (natural gas, oil, and coal) represents the primary exergy cost, as it accounts for the increasing exergy cost of fuels, and it can be

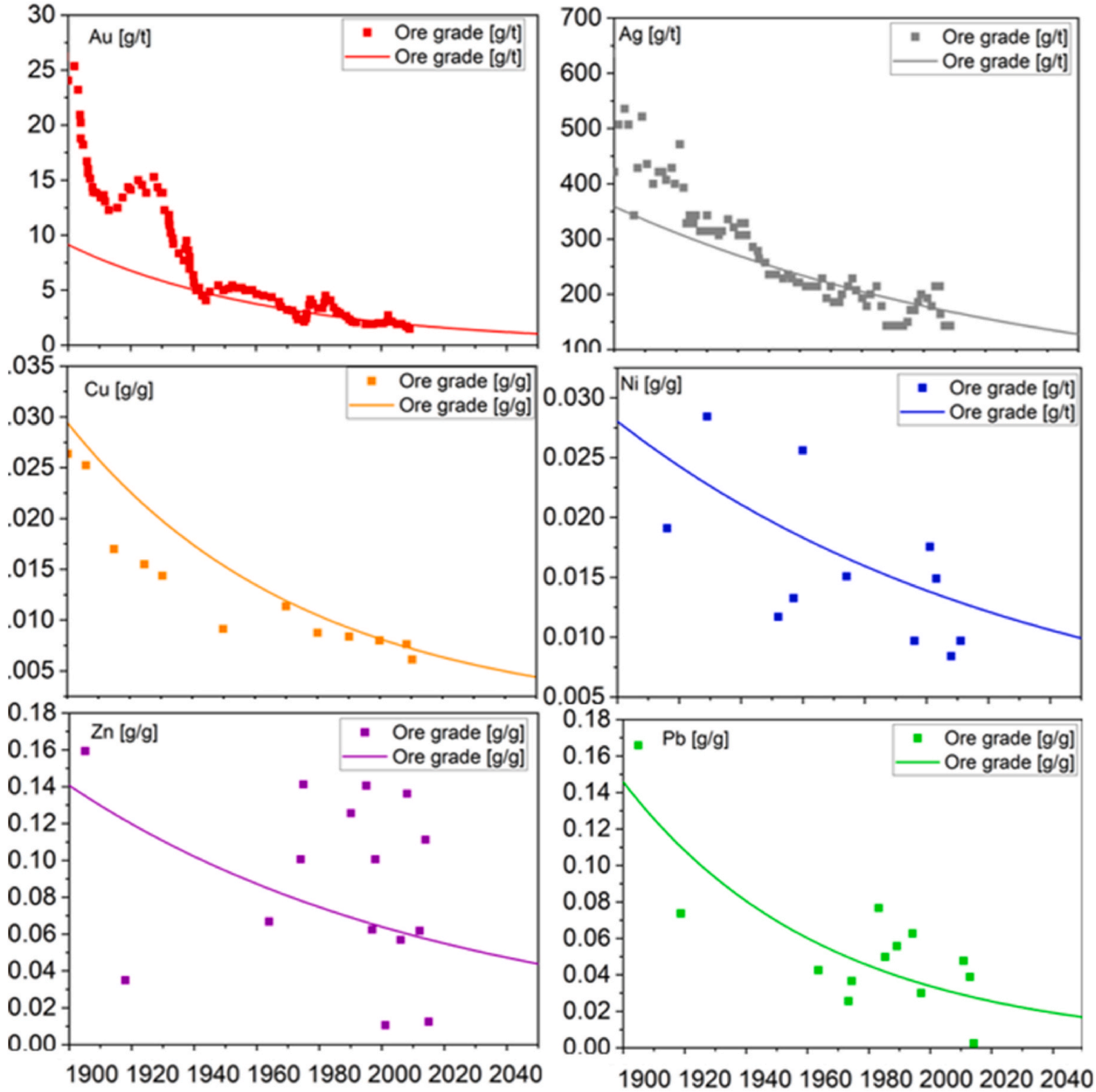

Fig. 2. Ore grade declining trends by year. Points represent studies, continuous line the trend used in this study.

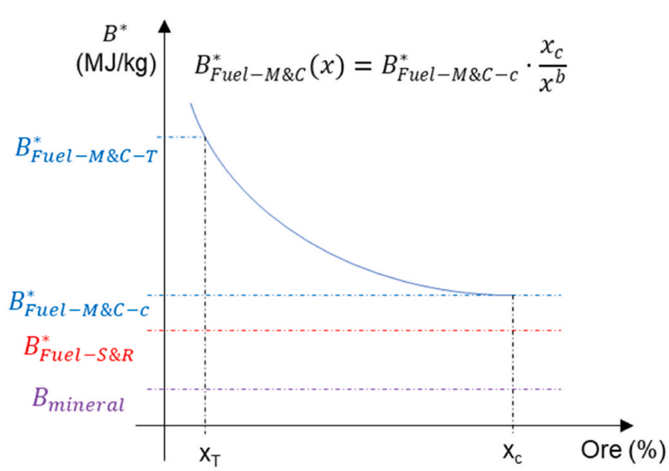

Fig. 3. Qualitative scheme for the calculation of the evolution of the energy cost with respect to ore grade.

calculated with equation (4):

$$B^*_{P-yr} = B^*_{F-yr-NG,Oil,Coal} \cdot B^*_{H2-yr} + B^*_{F-yr-ELEC} \cdot B^*_{ELEC-yr} \tag{4}$$

In contrast, the exergy cost associated with electricity, $b^*_{M-F(EL)-yr}$, refers to final exergy, as it does not include the exergy cost of its production and can originate from either renewable or non-renewable sources. Thus, to determine the primary exergy cost of metal extraction and refining, and distinguish its renewable or non-renewable origin, $b^*_{M-F(EL)-yr}$ must be converted into primary exergy cost. This is done using the evolution of the exergy cost of electricity.

Since the exergy cost of electricity varies significantly between 2020 and 2050 under the IEA's NET-ZERO scenario, multiple scenarios can be considered. Additionally, a scenario is included where fossil fuel consumption is replaced by renewable hydrogen. In this scenario, we assume a 1:1 energy substitution, meaning 1 MJ of fossil fuels is replaced by 1 MJ of hydrogen. Thus, we established four scenarios for the year 2050, depending on the exergy cost of electricity ($B^*_{ELEC-yr}$) and the exergy cost of hydrogen (B^*_{H2-yr}):

- Energy Mix 2020: $B^{*}_{ELEC-yr}$ remains constant. We obtained the values of $B^{*}_{ELEC-yr}$ of the year 2020 from (Torrubia, Valero et al., 2024). It describes a scenario in which the energy transition does not materialize, and therefore the current energy mix is maintained in the extraction and refining of metals.
- Electricity renewable: $B^{*}_{ELEC-year}$ evolve following the IEA NZE scenarios. We obtained this evolution from (Torrubia, Valero et al., 2024). This scenario represents a partial implementation of the energy transition in which only electricity is of renewable origin.
- Hydrogen PV: This scenario is equivalent to the previous one, but fossil fuels are gradually replaced by hydrogen following a linear trend until hydrogen fully substitutes fossil fuels by 2050. The hydrogen costs ($B^{*}_{H2-year}$) were obtained considering hydrogen has a photovoltaic origin (Torrubia, Lima et al., 2024). This scenario represents a complete integration of the energy transition by also replacing the direct use of fossil fuels with hydrogen.
- Hydrogen wind: It is the same as the previous one but using the costs of hydrogen obtained from wind energy (Torrubia, Lima et al., 2024).

This study assumes that renewable energies (electricity and renewable hydrogen) can be fully integrated into both mining and concentration operations and smelting and refining. However, achieving this integration presents several challenges, both technical (Igogo et al., 2021), economic and social (Pouresmaieli et al., 2023). For instance, mine locations in remote off-grid locations can hinder the use of renewable electricity (Igogo et al., 2021), as well as the need for larger spaces (Pouresmaieli et al., 2023). Substitution of fossil fuels with

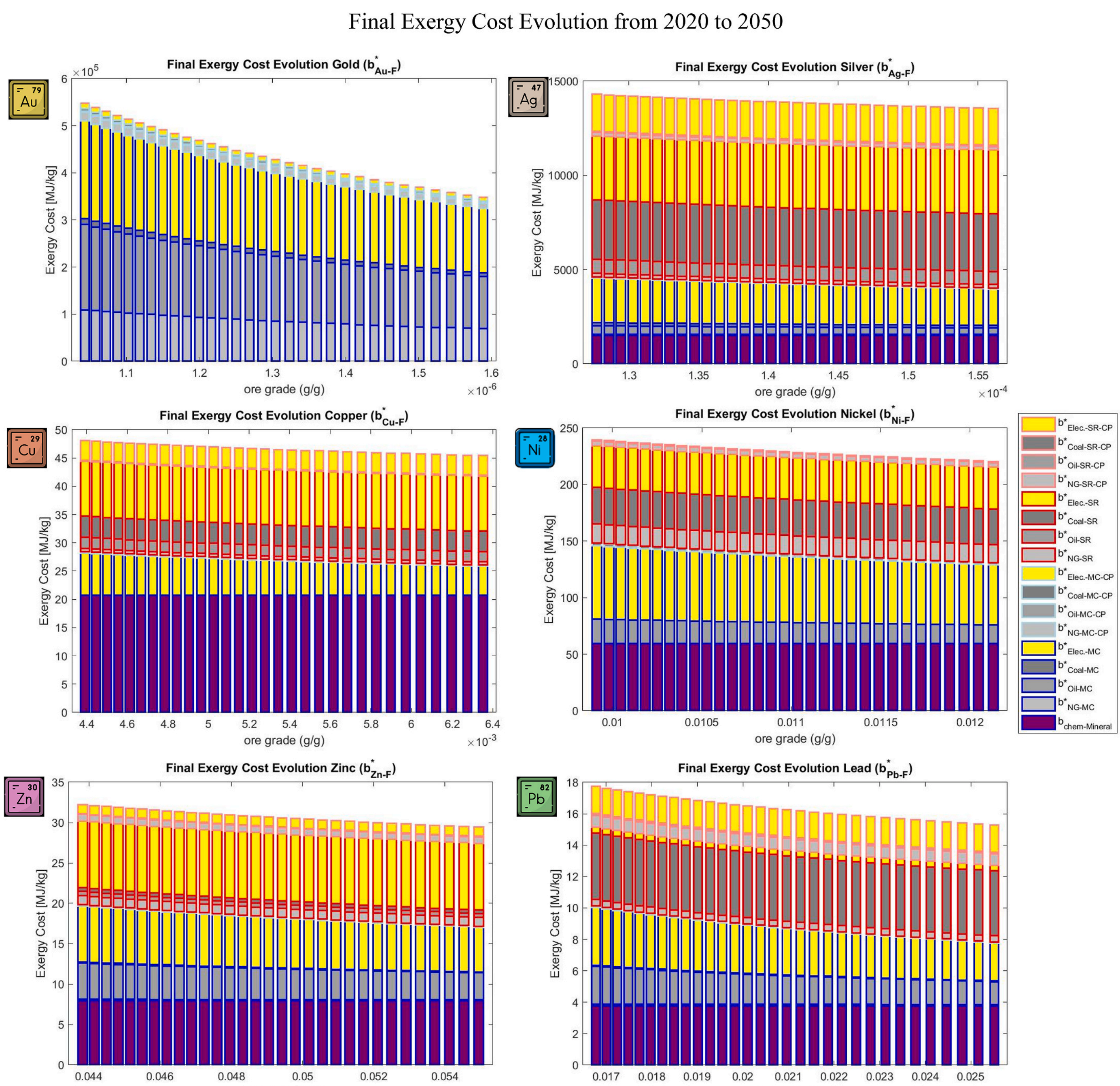

Fig. 4. Evolution of the final exergy cost according to the ore grade.

renewable hydrogen must be explored for each metal due to the change in metallurgical reactions (Harvey et al., 2022; McLellan et al., 2012). In addition, chemical industries must also integrate renewable energies due to the chemical reagents used in the metal industry (Harvey et al., 2022). Other factors, such as the lack of awareness among mine owners of the benefits of renewable energy adoption, the resistance of traditional management practices entrenched in the mining industry or the considerable initial investment costs, may also affect the integration of renewable energies (Pouresmaieli et al., 2023).

3. Results and discussion

3.1. Evolution of the final exergy cost

The methodology used to calculate the evolution of the final exergy cost (b^*_{M-F-yr}) allows for annual calculations. Therefore, Fig. 4 shows the yearly evolution of the final exergy cost between 2020 and 2050. In this figure, the minimum ore grade, represented on the horizontal axis, corresponds to the year 2050, while the maximum ore grade corresponds to the year 2020.

Fig. 4 focuses on Au, Ag, Cu, Ni, Pb, and Zn, as these metals have experienced a continuous historical decline in ore grade. The increase in the final exergy cost of metals observed is driven by two degradation factors: (1) the decline in the energy return on investment of fossil fuels and (2) the decreasing ore grade of these metals.

The classification of the exergy cost reveals that the MC and MC-CP stages are the only ones whose exergy cost increases due to the decline in ore grade. This is explained by the fact that a lower ore grade does not necessarily increase the energy consumption of the refining stages, since a fixed-grade concentrate is produced in the concentrating stage, regardless of the initial ore grade (Calvo et al., 2022).

Additionally, the mineral exergy remains constant over time, as the mineral used in the SR stage is considered unchanged. However, the exergy cost of fossil fuels increases slightly across all stages due to the decline in their EROI. Accordingly, the following results are obtained:

Between 2020 and 2050, the final exergy cost of:

- Au ($b^*_{Au-F-yr}$) increases by 57.5 %, as ore grade declines from 1.6 g/t to 1 g/t.
- Ag ($b^*_{Ag-F-yr}$) increases by 5.5 %, as ore grade declines from 156 g/t to 128 g/t.
- Cu ($b^*_{Cu-F-yr}$) increases by 5.8 %, as ore grade declines from 0.6 % to 0.4 %.
- Ni ($b^*_{Ni-F-yr}$) increases by 8.7 %, as ore grade declines from 1.2 % to 1 %.
- Zn ($b^*_{Zn-F-yr}$) increases by 9.5 %, as ore grade declines from 5.5 % to 4.4 %.
- Pb ($b^*_{Pb-F-yr}$) increases by 16 %, as ore grade declines from 2.5 % to 1.7 %.

Another consequence of this increase in exergy cost is the decline in EROI values, which decrease from 42 % for coal, 53 % for oil, and 44 % for natural gas during the same period. The magnitude of the increase in exergy cost depends on the contribution of chemical exergy and the SR and SR-CP phases to the total cost. The greater the contribution of these factors, the smaller the increase in exergy cost, as the key driver of this increase is the MC and MC-CP stages. Because gold is a native metal, and its entire final exergy cost is attributed to the MC and MC-CP stages, it shows the highest increase (57.5 %). On the other hand, copper and silver, which have high contributions from mineral exergy and the SR and SR-CP stages (88 % and 81 % in 2020, respectively), show the smallest increases (5.8 % and 5.5 %).

Final exergy costs always increase as ore grade decreases when the origin of primary energy is not considered. However, depending on the source of primary energy, the primary exergy cost can be lower even if ore grade declines. In Fig. 4, electricity is presented as final energy, without accounting for the natural resources used in its production, which can vary significantly. For example, electricity generated from coal has an average non-renewable exergy cost of 3, meaning that 3 units of non-renewable exergy are required to produce 1 unit of electricity. In contrast, a solar panel only requires 0.2 kWh of non-renewable exergy to generate 1 kWh of electricity.

The results obtained have been compared with data collected from literature to validate the findings. This comparison is illustrated in Fig. 5, extending the minimum ore grade to enhance the representation. It is essential to mention that the origin of the data collected from the literature is different. For instance, the data from gold and copper comes from data obtained from real mines, in the case of Au from Australian mines, while the case of Cu from mines worldwide (Calvo et al., 2016; Mudd, 2007). On the other hand, lead and zinc are calculated through simulations carried out a specialized software (Magdalena et al., 2021b). Then, nickel has been calculated based on the processes to refine metals from mines with different ore grades (Wei et al., 2020). Last, the case of silver is complex to analyze since it is a by-product of Pb-Zn mining. Thus, significant variations in the reported ore grades are noted, ranging from 128 g/t to less than 1 g/t.

As it is shown, a comparison has been made between bibliography data (points in the chart) and this study. It is seen that this comparison has a strong correlation for almost every metal analyzed, driving to validate the methodology applied despite its limitations. Both the lines (representing the results of this study) and the points (literature data) generally exhibit an exponential increase in exergy consumption as ore grade concentration decreases.

The observed differences can be explained by the fact that literature data are based on energy, whereas this study focuses on exergy costs, which is always higher than energy. Specifically, when analyzing each metal, the evolution of the final exergy cost for Pb, Zn, and Ni aligns more closely with the literature data. This may be due to the fact that the literature values for Ni, Pb, and Zn were obtained using computational methods.

In the case of Cu, the final exergy cost is observed to be lower than the literature values for the same concentration. However, the overall exponential trend remains consistent. For Ag, the calculated exponential curve closely matches the trends reported in the literature. Finally, for Au, the evolution of the final exergy cost is similar to the literature data, despite a greater tendency for lower energy costs in previous studies.

The exponential increase in exergy consumption observed in this study is a direct consequence of the Second Law of Thermodynamics and can be attributed to several factors. Lower-grade ores require processing larger quantities of material to obtain the same amount of metal, leading to higher energy consumption in extraction, crushing, milling, and beneficiation processes (Norgate et al., 2010; Norgate and Haque, 2010). Additionally, lower-grade ores typically necessitate more energy-intensive separation and concentration techniques to isolate the desired metal, further increasing exergy consumption.

3.2. Primary exergy cost

While the final exergy cost takes into account the sum of exergy inputs along the process to obtain a metal, the primary exergy cost decouples the final exergy into different energy sources. Accordingly, this study divides the final exergy cost into various types of energy sources, and projects the primary energy demand until 2050, offering a more comprehensive understanding of energy consumption patterns in different metal extraction processes. It is key to disaggregate the exergy cost since the exergy of the non-renewable energy can be used only once. Consequently, this disaggregation is essential to understand how much non-renewable and renewable energy is used for these metals and which will be the origin of this energy in 2050.

Hence, Fig. 6 has been developed to illustrate the exergy costs associated with the production of various metals under different primary energy scenarios explained in the methodology. These scenarios

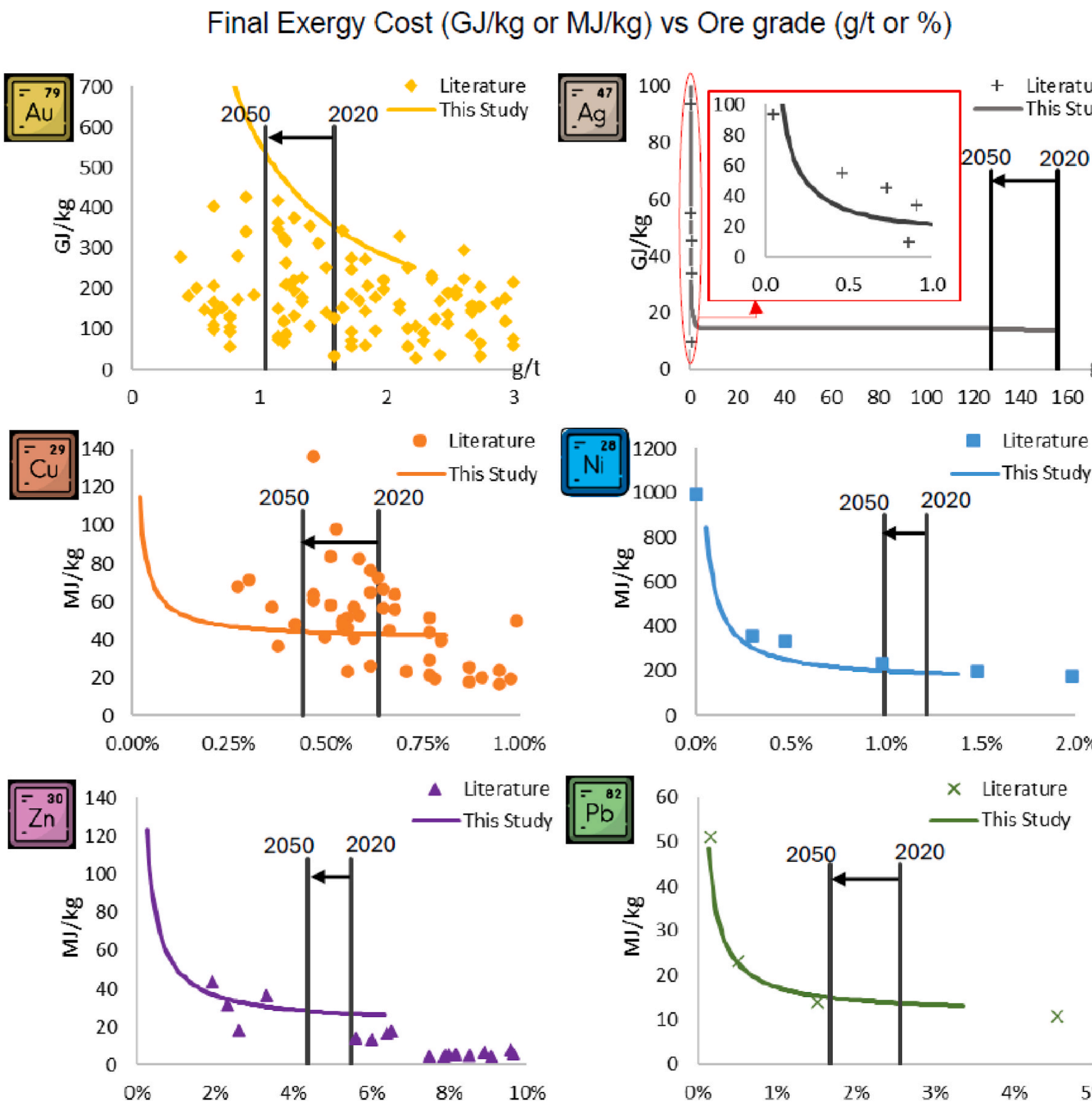

Fig. 5. Comparison of the results obtained in our study with bibliography (Calvo et al., 2016; Magdalena et al., 2021b; Mudd, 2007; Sverdrup and Ragnarsdottir, 2014; Wei et al., 2020). Note that there is no much empirical data available in the bibliography and some metals have been validated just with a few points.

compare the primary energy mix from 2020 with various possible energy mixes projected for 2050. The scenarios proposed for the projection until 2050 (electricity renewable, hydrogen PV, and hydrogen wind) include the transition to renewable energy sources and the integration of hydrogen into the energy mix, produced through both non-renewable energy and green hydrogen.

Comparing the first two columns for each metal (2020 energy mix vs. projected 2050 mix), we see an increase in exergy cost. This is caused by the fact that the energy sources remain the same, but the ore grade is lower. Looking at the other scenarios, the transition to renewable energy and renewable hydrogen generally helps reduce exergy costs in metal production. This is because today's energy mix mainly relies on electricity from non-renewable sources. If we replace this with renewable electricity, the energy cost of metal extraction decreases. Since fewer primary resources are needed to produce electricity, its exergy cost also goes down. However, in scenarios where hydrogen is integrated, exergy costs tend to increase. Still, despite total exergy use rises, the use of non-renewable exergy decreases, helping to preserve natural resources.

The reduction in energy costs for each metal depends on how they are produced and the energy needed for extraction and processing (excluding chemical exergy, which stays the same in all cases). For example, Cu and Zn follow a similar pattern. By switching to green electricity by 2050, their total exergy costs could drop by about 50 %. However, even in this scenario, they still use some coal, oil, and natural gas, mainly because mining relies on diesel for transportation. In the last two scenarios, hydrogen replaces fossil fuels, reducing non-renewable energy use, especially when the hydrogen comes from wind power. This change slightly raises the total exergy cost (by 4 % for Cu and 16 % for Zn). However, the use of non-renewable exergy drops by more than 60 % for both metals, which helps conserve natural resources.

On the other hand, Pb, Au, Ni, and Ag rely more on oil, coal, and natural gas compared to other metals. Even when electricity is produced from renewable sources, these fossil fuels still account for a large share of the total energy costs—around 60 % for Ni and Ag, and 80 % and 95 % for Pb and Au, respectively. Despite this, transitioning to renewable electricity helps reduce energy costs for each metal. Specifically, Ni and Au experience a reduction of about 60 %, Ag by 50 %, and Pb by 45 %. However, in the last two scenarios, where hydrogen replaces non-fuel energy sources, the final exergy costs increase compared to the renewable electricity scenario. In these cases, Pb sees a 42 % increase, Au 51

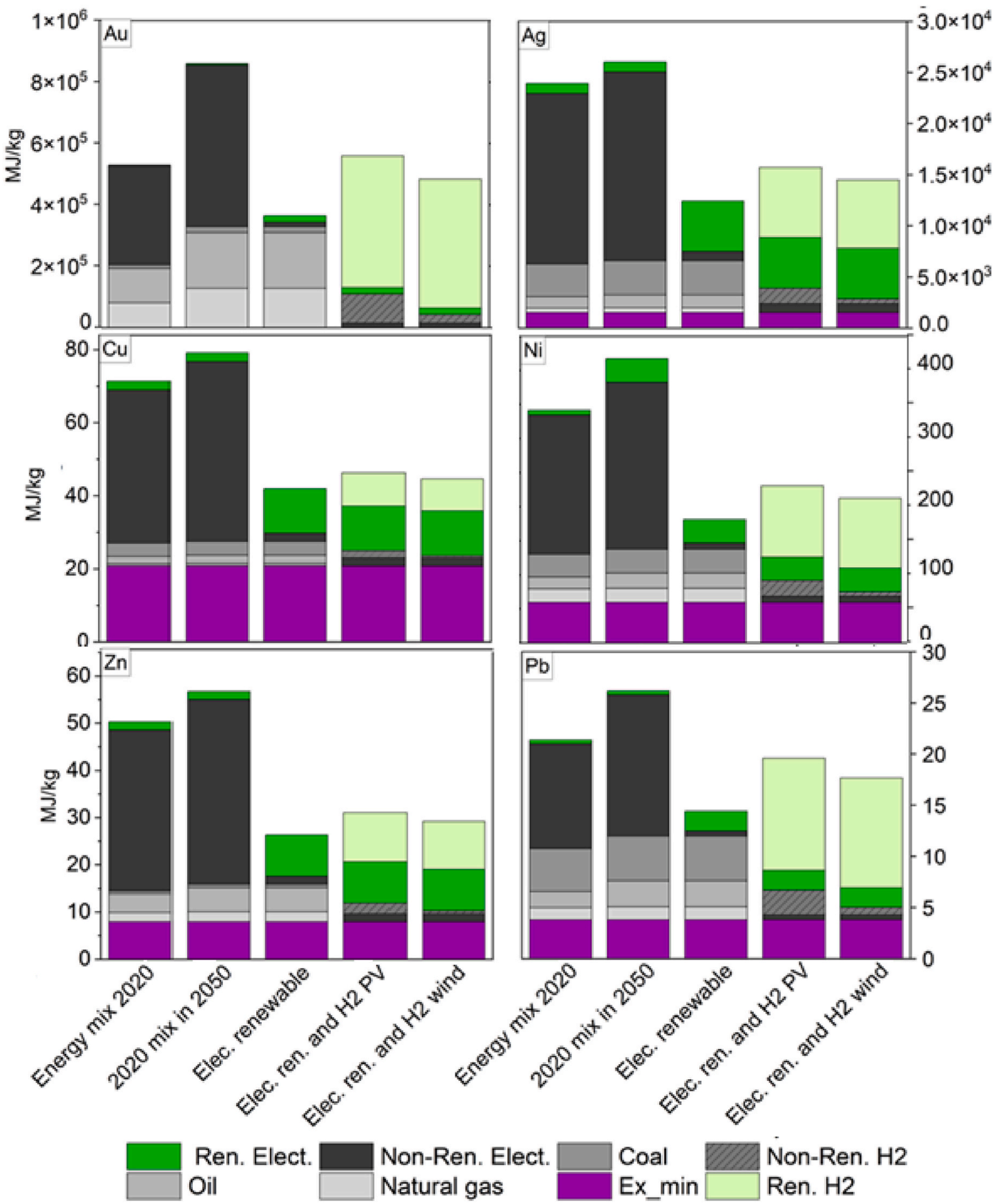

Fig. 6. Primary energy consumption for different metals in the five scenarios proposed.

%, Ni 35 %, and Ag 22 %. Although the final exergy costs increase in the last two scenarios, the use of non-renewable exergy is significantly reduced. Pb decreases by more than 70 %, Au by over 53 %, Ni by around 70 %, and Ag by more than 50 %.

The analysis reveals a clear trend toward reducing exergy costs with the adoption of renewable energy and the use of renewable hydrogen. While the scenarios involving hydrogen do not have the lowest exergy costs, it is important to consider that these costs originate from renewable sources. The scenario with the lowest energy costs still depends on oil, coal, and natural gas—resources that are finite and will eventually be depleted. In contrast, hydrogen produced from photovoltaic and wind farms offers a sustainable alternative. This is why it is essential to decouple the final exergy cost to distinguish non-renewable exergy and evaluate its impact on the energy transition projected for the coming decades. In this way, natural resources can be preserved, and non-renewable exergy can be minimized. The shift from the 2020 energy mix to a future with a greater share of sustainable energy sources presents a clear path toward improved energy efficiency and long-term sustainability in metal production.

3.3. Future projections for exergy costs

Although 2050 is considered a benchmark year for achieving net-zero emissions (International Energy Agency, 2021) metal extraction will continue beyond this point. While technological advancements and expanded metal recycling capacity are expected to meet growing demand, (including the recovery of metals from tailings, see the work of Magdalena et al. (2021a)), declining ore grades, a trend projected to continue post-2050, will escalate the energy intensity of metal recovery. Notably, recycled metals offer a dual advantage: they reduce the need for primary resource extraction and require less energy than mining, particularly for very low-grade ores. Nevertheless, recycling alone cannot eliminate primary extraction, as smelting innovations may only partially offset the rising energy demands of decreasing ore quality.

Additionally, preserving non-renewable resources remains crucial, as these resources have a higher exergy cost than renewable sources. To illustrate this, Fig. 7 presents the evolution of non-renewable exergy for ore grades projected until 2050, as well as for lower concentrations that may be encountered in mines beyond that year. This projection has been calculated for four scenarios. The first scenario assumes the 2020 energy mix, while the other three incorporate electricity generated from renewable sources. The third scenario also includes hydrogen produced via photovoltaic energy, and in the final scenario, hydrogen is generated using wind power.

It can be seen that from a general perspective, there is a significant short-term (until 2050) benefit for each metal when renewable energy sources are incorporated. However, in the long term, this benefit is reduced considerably due to the extremely high exergy cost. Moreover, Moreover, the non-renewable exergy cost associated with renewable technologies is enough to increase the destruction of non-renewable

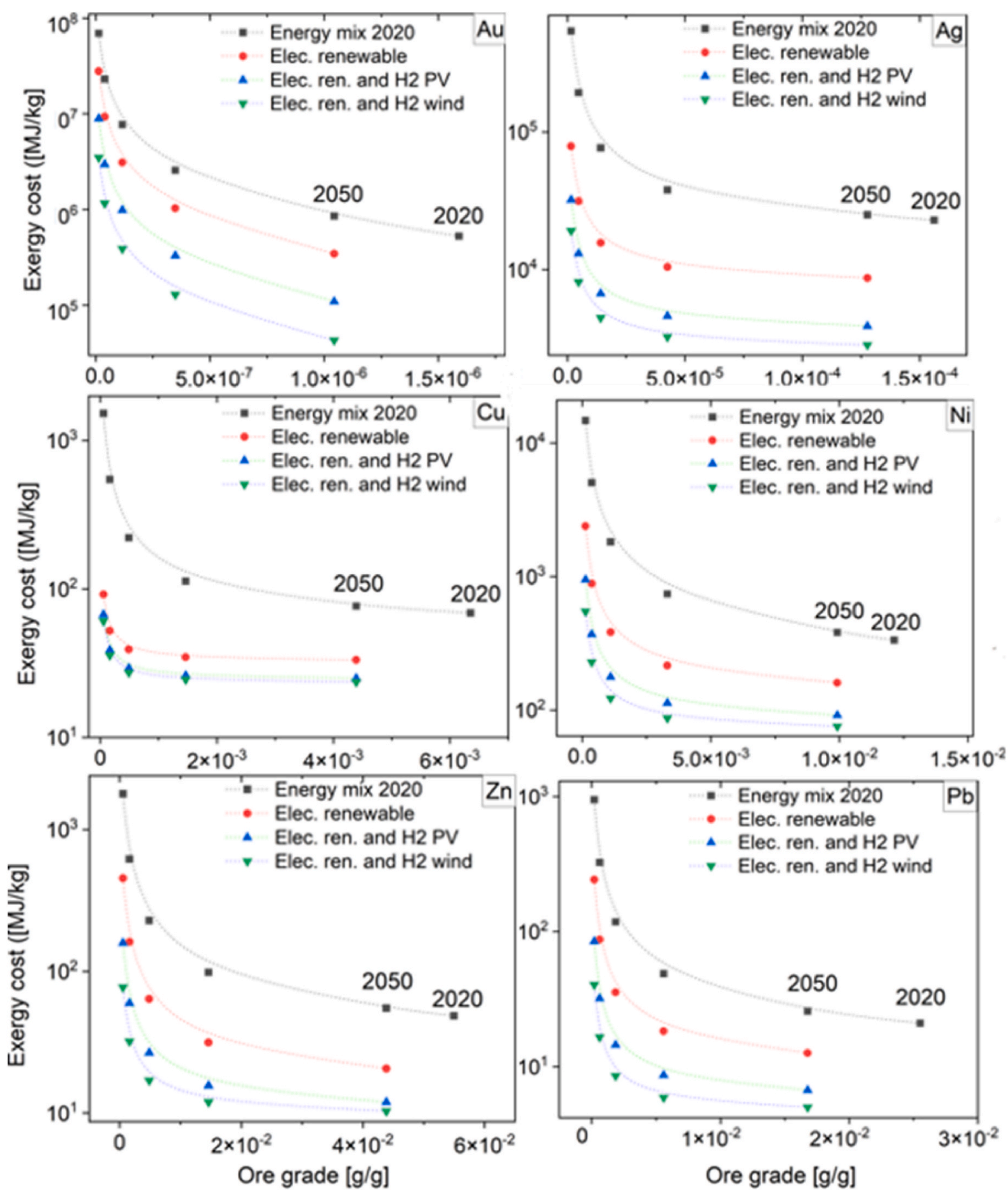

Fig. 7. Non-renewable exergy cost for the metals assessed for future lower ore grades.

exergy in the form of indirect resources.

Copper serves as a clear example of this situation. The beneficiation process for copper is largely dependent on electricity, while the refining only requires small quantities of fossil fuels. Chalcopyrite, which contains high chemical exergy, is the primary ore used. Therefore, since the increased electricity demand associated with lower ore grades can be met with renewable electricity, there is a rise in the non-renewable exergy cost of 66 % (from 2050 to the last point on the left of the red line). Furthermore, the influence of integrating hydrogen is minimal due to its low impact on the energy mix for copper extraction. This is mainly because hydrogen replaces oil, coal, and natural gas, fossil fuels that are not extensively used in copper recovery.

Gold presents an opposite trend compared to copper. Although the lines are close, it is important to note the logarithmic scale, which indicates that the application of green energy sources can significantly impact the exergy cost, potentially reducing it by up to 97 % when hydrogen produced by wind farms is included (representing the high dependency in fossil fuels, opposite to copper that relies mainly on electricity). However, as ore grades decrease, the scenarios converge, with each scenario remaining within the same order of magnitude. Additionally, it is noteworthy that the energy cost for gold increases by two orders of magnitude from the initial point in every scenario, with the final point reaching the same order of magnitude as the projected 2050 trend for the current non-renewable exergy cost. Since the gold concentration is already very low, the exponential shape for this metal is more noticeable. Therefore, by comparing scenarios, gold contains the smallest reduction in terms of concentration, when it is compared with other metals. Still, this value is very high, since the non-renewable exergy cost with hydrogen scenarios would be the same than the renewable electricity scenario in 2050, reducing the concentration of this year by 77 %.

As it has been seen, the ability to measure exergy and distinguish between renewable and non-renewable resource origins provides a comprehensive energy-centric view of the impact of energy transitions on metal extraction and beneficiation. This perspective is crucial for making future projections and identifying areas that require intensified research. Our analysis reveals that while the introduction of renewable energies in mining and metallurgy can offset non-renewable exergy costs in some cases, it may not be sufficient in others. Ultimately, the ore grade becomes the dominant factor influencing costs. Still, mining companies are adopting renewable energy integration to reduce reliance on fossil fuels. BHP and Rio Tinto, for instance, are deploying solar photovoltaic, wind, and battery storage systems, while the Escondida mine in Chile operates on 100 % renewable electricity, cutting emissions, lowering operational costs, and preserving finite natural resources (Li et al., 2024). However, fully decarbonizing mining remains challenging, particularly in remote extraction sites where energy infrastructure is limited.

Notably, electrification or renewable hydrogen adoption is easier in metallurgy, which typically takes place in industrial centers with better access to clean energy. In contrast, mining operations often face logistical barriers due to their isolated locations. Pilot projects, such as hydrogen-powered mining trucks, highlight progress in this area, but heavy machinery and transport remain the sector's hardest-to-abate emissions sources.

Additionally, the benefits of integrating green hydrogen are remarkable, as observed when comparing scenarios. However, while production costs account for the renewable energy needed to manufacture electrolyzer materials, they exclude storage and transport, meaning actual costs will be higher. Storage and transport systems, which are new technologies, vary significantly depending on the project. For instance, hydrogen can be transported by truck or pipeline, with substantial cost differences. As our study is not location-specific, its focus is to assess how renewable energy use in mining affects resource use, measured in exergy. For instance, compressing hydrogen from 0 to 700 bar increases the exergy cost by about 10 %. However, this pressure is mainly for mobility applications; industrial hydrogen typically requires lower pressure. Due to such uncertainty, we chose not to include these values, though they will be considered in future work.

Regarding the sensibility of the model, equations (1)–(4) describe a linear model without feedbacks, so the error transmission is also linear. This means that no perturbations larger than the error assumed in the sensitivity analysis would be expected, as demonstrated in similar models (Torrubia et al., 2023b). Moreover, the scenario analysis can be extended to include policy-driven pathways, such as the introduction of carbon taxes or renewable energy subsidies. These measures can significantly influence the economic viability of metal production by altering energy costs and incentivizing cleaner technologies, thereby shaping future resource demand and sustainability outcomes.

It is also important to note that our study focuses only on energy considerations. Other critical factors such as water usage, which could become a limiting resource (e.g. the extraction of Cu and Li in Chile (Moraga et al., 2023)), and the extensive land disruption associated with mining activities, which significantly impacts biodiversity in vulnerable regions, were not accounted for. These environmental aspects (water, land impact, use of chemicals, waste management) must be integrated into future analyses to develop a complete understanding of the sustainability of mining practices. Moreover, new scenarios should be incorporated in future works modifying key parameters such as the ore grade of the metal, or the energy regional structure that could limit the energy transition. Finally, incorporating future sensitivity analysis by incorporating scenarios with ultra-low ore grades or elevated recycling rates can strengthen the reliability of assumptions underpinning energy transition pathways.

4. Conclusions

The demand for metals is significantly contributing to the decrease in ore grades. The decline in ore quality makes the extraction process more energy-intensive and costly. Within this framework, energy is considered as a major constraint in mining and metal production, with significant costs and environmental impacts, particularly noticeable during the mining and concentration stages. The industry's reliance on fossil fuels, such as coal, gas, and oil, exacerbates these impacts. Lower ore grades require larger amounts of material to extract and process, leading to higher energy usage and intensifying the energy constraint.

Renewable energy sources have the potential to reduce the carbon footprint of mining operations. Despite the slow transition towards renewable energy, it is possible to reduce emissions in the mining sector. Accordingly, the feasibility of this transition has been assessed for various metals. Through the methodology employed, we were able to estimate not only the future exergy costs for certain metals, such as Cu, Pb, Zn, Au, Ni, and Ag, but also to assess the impact of the energy transition with the primary energy consumption on the final exergy costs.

The current energy use has been disaggregated to evaluate different primary energy sources. Scenarios for integrating renewable energy into the mining and metallurgical sectors have been created. The current energy mix has been compared with potential future energy sources, including renewable energy and hydrogen. The results indicated that transitioning to renewable energy sources, particularly renewable electricity and hydrogen, can significantly decrease the exergy costs associated with metal production. The proposed scenarios reveal that using a combination of renewable electricity and fossil fuels results in a lower exergy cost compared to scenarios incorporating hydrogen alongside renewable electricity. Despite the growing adoption of hydrogen technology, this transition remains crucial as it significantly reduces fossil fuel consumption, leading to exergy cost reductions of 60 % for Cu and Zn, 70 % for Pb and Ni, 53 % for Au, and 50 % for Ag. This decrease is key due to the decrease reliance on finite fossil fuels and helps preserve natural resources.

In the short term, the integration of renewable energy sources shows significant benefits across most metals. However, as ore grades decline over time, these benefits are substantially reduced. This highlights the necessity for continuous advancements and optimization in renewable energy applications specific to the mining sector and the recyclability of metals. Metals such as copper, which benefit greatly from electricity-based beneficiation processes, exemplify the potential advantages of renewable energy integration, increasing only 40 MJ/kg the non-renewable exergy cost from 2050 to a future with much lower ore grades. In contrast, metals like gold, which is more dependent on fossil fuels, demonstrate that, despite substantial reductions in exergy costs with green energy adoption, the influence of declining ore grades cannot be overlooked. In a conservative scenario where green hydrogen is not integrated, it is observed that a decrease in ore grade results in the same non-renewable exergy cost as in 2050. To achieve that, this reduction must be 75 % for Pb, 81 % for Zn, 55 % for Au, 82 % for Ni, and 87 % for Ag.

The projected exergy costs for the analyzed metals show that the transition to green mining is essential to reduce future impacts associated with the mining industry. This study highlights the significant role of primary energy in the extraction and beneficiation stages. However, while our study assesses these impacts, the feasibility of introducing the proposed amount of renewable energy remains uncertain. Increasing recycling rates can play a key role in mitigating the decline of ore grades, as higher recycling levels reduce the demand for virgin raw materials, slowing down the depletion of high-quality ores. However, several challenges remain, including the integration of hydrogen-based electricity, advancements in emerging energy technologies, and improvements in efficiency, particularly in remote mining areas where access to renewable energy is limited. Additionally, this study has certain limitations, such as its regional scope, which may not fully capture the variability in mining conditions worldwide, and grid energy dependencies, which influence the feasibility of renewable integration. Addressing these challenges through further research and technological development will enhance the feasibility of large-scale renewable energy adoption in mining.

At the same time, the findings provide practical guidance for integrating renewable energy into the sector, supporting industry decision-makers in transitioning to more sustainable operations while complying with increasingly stringent environmental regulations. Additionally, they could stablish the groundwork for policymakers to develop incentives that drive the sector's decarbonization, ensuring a more sustainable and resilient mining industry.

CRediT authorship contribution statement

Ricardo Magdalena: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Investigation, Formal analysis, Data curation. **Jorge Torrubia:** Writing – review & editing, Supervision, Methodology, Data curation. **Alicia Valero:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

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Data availability

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

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Glossary

Cu –Copper
Pb –: Lead
Zn –: Zinc
Au –: Gold
Ag –: Silver
EROI –: Energy Return On Investment
Ni –: Nickel
LCA –: Life Cycle Assessment
MC –: Mining & Concentration
MC-CP –: Mining & Concentration – Chemical Production
SR –: Smelting & Refining
SR-CP –: Smelting & Refining – Chemical Production
MJ/kg –: Megajoule per kilogram

b*M−F –Final Exergy Cost
IEA –: International Energy Agency
PV –: Photovoltaic
NET-ZERO –: Net-Zero Emissions Scenario