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Optimizing Mineral Extraction and Processing for the Energy Transition: Evaluating Efficiency in Single versus Joint Production

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Abstract

The efficient extraction and processing of ores into metals is key to clean energy transition technologies. This study compares *single* metal (e.g., copper) producers with *joint* metal (e.g., copper and cobalt, copper and nickel) producers in the mining and metallurgical sectors. Drawing from a theoretical framework grounded in optimization theories, we develop an economic model to characterize and compare the average cost of processing ore for these two types of firms. Additionally, we use empirical data from 427 mining projects worldwide to analyze the average cost of processing ores to produce copper, cobalt, and nickel, either as single or joint products. We find that the relative output elasticity of the ore is key to governing the response of average costs to changing model parameters such as unit costs and taxes, total factor productivity, metal demand, and the volume of the ore processed. We also derive conditions under which joint metal production can offer cost savings compared to single metal production, showcasing the economic advantages of multiple metal production to advance energy transition goals. By integrating theoretical modeling with real-world data, this study offers unique insight into cost dynamics, operational efficiency, and strategic decision making in mineral extraction and processing, with implications to optimize industry profits.

Keywords: critical minerals, energy transition, nickel, cobalt, ore, average cost, mining

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1 Introduction

The efficient extraction and processing of ores into metals play an essential role in several clean energy transition technologies. Metals such as copper, nickel, indium, platinum, and cobalt are important inputs for technologies such as wind turbines, solar panels, concentrated solar power, fuel cells, energy storage systems as well as for electric mobility (Fikru and Kilinc-Ata, 2024; Watari et al., 2020). However, the production of certain metals and materials (sometimes referred to as *critical* due to supply chain constraints) is often limited by technical challenges, high processing costs, and price volatility (Romani and Casoli, 2024; Bastianin et al., 2023). On the one hand, *base metals*, such as copper, iron, and aluminium, are widely used in construction, electrical wiring, and various industrial applications. Thus, they have relatively well-established processing technologies and low cost of treating and refining. On the other hand, *critical metals* such as cobalt or rare earth elements (REEs) (Watari et al., 2020) tend to be used in very small quantities and are hard-to-substitute inputs in the manufacturing of digital and green technologies (unlike copper) due to their specific chemical, electrical, and mechanical properties (Tabelin et al., 2021). As demand for both base and critical metals is rising with progress in the energy transition, mining and metallurgical companies, as well as countries willing to strengthen their domestic supply chains, have the imperative of optimizing their mineral production processes.

The literature on the mineral-energy nexus focuses primarily on the processing of ore to produce individual critical metals in isolation. In fact, individual metals are studied in terms of supply chain dynamics (Junior et al., 2021; Costis et al., 2021), geopolitical and governance factors (Sovacool et al., 2020; Church and Crawford, 2020), and implications for a mineral-intensive energy transition (Nwaila et al., 2022). However, not all metals are produced as single products. Many are obtained through joint production processes, where a single ore serves as a common input to produce multiple metal commodities. The multiple metals obtained from a joint production system are sometimes referred to as *co-products* (see a report by the Congressional Reserach Service (2024)), or *host* versus *co-host metals* (Watari et al., 2020). Processing the ore typically yields a base metal and one or more additional metals. For example, mineral-containing ores can be inputs for copper as a base metal, and additional processing yields critical metals such as tellurium, arsenic, antimony, and bismuth (Moats et al., 2021). Rare earth elements (REEs) are also often found in a common ore, where a typical mineral deposit could contain up to five REEs at relatively high concentrations (McNulty et al., 2022). Looking at the North American perspective, at least 24 of the 50 critical minerals identified by the US government are predominantly produced as joint products (Nassar et al., 2015; Nassar and Fortier, 2021; Moran-Palacios et al., 2019).

In a mineral-intensive energy transition, where demand for both base and critical metals is rapidly increasing, studying joint metal production to assess mineral criticality becomes extremely important (Fikru and Kilinc-Ata, 2024). However, there are only a limited number of studies that model a joint production system to examine the efficiency, productivity and economic viability of metal production for the energy transition (Bigerna and Campbell, 2024; Fikru and Awuah-Offei, 2022; Kim, 2020). Our study addresses the literature gap by developing an economic model to characterize costs. We also conduct an empirical analysis to compare the average cost of processing ore for single and joint metal producers, thus providing a comprehensive framework for evaluating the economic viability of base and critical metal production. By examining the cost implications of different production strategies, we provide insights into how mining and metallurgical firms can optimize their operations to minimize costs and enhance profitability.

First, we model two firms engaged in a range of activities, from upstream operations (exploration, mining, and beneficiation) to the midstream stages of the supply chain (smelting, refining). The two firms are: a single metal producer, which processes ore to produce one metal (e.g., a base metal like copper), and a joint metal producer, which processes ore to produce two metals simultaneously (e.g., base and critical metals). The analysis includes constrained optimizations, the derivation of conditional ore demand, and the characterization of optimized average costs for both types of firms.

Second, the study provides an empirical analysis of the costs of processing ores to produce copper (Cu), cobalt (Co), and nickel (Ni), based on data from 427 mining projects worldwide. This data includes the average cost of processing ore and the volume of ore processed. Among these, 62 sites are joint metal producers (producing copper and cobalt as Cu-Co, cobalt and nickel as Co-Ni, copper and nickel as Cu-Ni, or all three metals as Cu-Co-Ni), while the remaining 365 sites are single metal producers. This forms the basis for comparing site-level average costs across countries, metal types, and single-versus-joint producer types. Patterns in the data are interpreted using the solutions from the constrained optimization model. By combining theoretical optimization models with empirical data, the study generates unique data-driven insights into the cost dynamics, operational efficiencies, and strategic considerations of mining and metal processing activities.

The paper is structured as follows. Section 2 develops the theoretical model with some simplifying assumptions. Then, Section 3 presents results from the more detailed model, which characterizes average costs for single and joint metal producers. Section 4 offers an empirical analysis based on mining site-level data collected worldwide. Using the theoretical framework and model results, patterns in data are interpreted by comparing the cost of operation of single versus joint metal producers. Section 5 concludes with policy implications and some questions for future work.

2 Theoretical Model

We develop an economic model to compare the average cost of processing ore when the average firm produces a single base metal versus when co-producing an additional metal via a joint production technology. We consider a generic firm that is involved in the extraction (i.e., mining the ore from the ground) and the processing (i.e,. treating and refining) of ores into metals, in an integrated operation that involves both upstream and midstream stages of the metal supply chain.

In lights of this, we model two types of firms. The first type of firm is engaged in the extraction of a mineral ore to produce only one individual metal (*single metal producer)*. For example, the firm can mine copper ore deposits which are then treated to produce the metal copper as a single product. The second type of firm is engaged in the extraction of the same mineral ore, that is then treated to produce two metals jointly (*joint metal producer*) (Bigerna and Campbell, 2024). Following Jordan (2018), we use the term *joint* products, since the second metal (e.g., cobalt) needs to be intentionally produced by processing the common ore from which a base metal (e.g., copper) is produced.

2.1 Metal production functions

Depending on whether the firm employs single or joint metal production, the firm produces either one or two metals, respectively. The production of metals is modeled following the production functions, $x_i = f_i(x_o, x_{n,i})$, where $i = 1$ for a single metal producer and $i = 1, 2$ for jointly produced metals. The ore volume (x_o) is a common input that is treated and refined to produce one (x_1) or two metals (x_1, x_2). In addition, we consider numeraire inputs ($x_{n,i}$) that are needed in the mining and mineral processing stages (e.g, reagents for treating ore, energy, labor, etc.). The price of numeraire inputs is set to one to focus on demand for the common ore.

Following previous studies (Fikru and Awuah-Offei, 2022), we consider two Cobb-Douglas metal production functions given by $x_1 = A_1 x_o^{\alpha} x_{n,1}^{\beta}$ and $x_2 = A_2 x_o^{\theta} x_{n,1}^{\eta}$ where A_1, A_2 are technical efficiency indicators for processing ore into metals (*total factor productivity*). Returns to scale of metal production is represented by $\alpha + \beta$ for metal x_1 and $\theta + \eta$ for metal x_2 . The parameters α, θ represent the *output elasticity of ore*, holding the numeraire inputs constant. They indicate how efficiently inputs (ore) can be transformed into output (metals). That is, the percentage change in the production of the two metals, respectively, that results from a one percent change in the amount of ore processed or the responsiveness of metal production to changes in the amount of ore processed. If α, θ are high, this suggests that the amount of ore processed is a major determinant of metal production efficiency (e.g, additional ore extracted boosts metal production).

We define $\epsilon_1 = \alpha/\beta > 0$ to represent the ratio of output elasticity of ore to output elasticity of numeraire input for the first metal and $\epsilon_2 = \theta/\eta > 0$ for the second metal (that is, *relative output elasticity of ore*). If $\epsilon_i > 1$, for each percent increase in the ore, a firm is able to produce the i^{th} metal in a relatively more proportional way than when the numeraire input increases by the same unit and vice versa. For example, when $\epsilon_i > 1$, a one percent increase in ore can produce more metal than a one percent increase in energy use. Conversely, when $\epsilon_i < 1$, a one percent increase in energy produces more metal (e.g., through further processing of existing or already mined ore) than a one percent increase in ore. In addition, if ϵ_i is relatively high, investing more in the extraction of ore might be more effective than upgrading machinery, hiring more workers, or using more energy power. Conversely, if ϵ_i is relatively low, improving capital inputs or other numeraire inputs like energy might yield better returns in terms of metal production efficiency.

These technical parameters (i.e., the ϵ_i measuring relative output elasticity of ore) play a crucial role for optimizing production strategies in the metal extraction industry, by indicating the relative importance in the amount of ore processed as a major determinant of metal production efficiency. Finally, if $\epsilon_1 > \epsilon_2$, then the first metal responds relatively more to changes in the volume of ore input processed than the second metal. For example, base metals such as copper may have a higher ϵ_i (using more ore translates to increasing copper production at a higher rate) compared to critical metals such as cobalt or REEs.

2.2 Deriving conditional ore demand

The firm incurs the cost of ore extraction and processing, which is assumed to be linear and given by $C(x_o) = cx_o$, $c > 0$, $C(0) = 0$, where c is a constant cost parameter. The firm is required to pay taxes per unit of ore processed. This tax is represented by $\nu \geq 0$ (expressed in terms of dollar per ton of ore), which is assumed to be exogenous to the firm. For example, this can be in the form of a per unit royalty (for each unit of ore extracted from the ground/surface) or in the form of rent payments. Thus, total tax payment is given by νx_o. Consequently, the firm's expenditures or costs are given by $(c+\nu)x_o + \sum x_{n,i}$, where $i = 1$ for the single producer and $i = 1, 2$ for the joint metal producer.

The firm makes decisions on the volume of ore needed given its costs (tax payments as well as the cost of ore extraction and treatment) and given the demand for metals. The firm's problem is solved using a constrained optimization procedure under two scenarios: when the firm is a single metal producer and when the firm is a joint metal producer. Expenditure or cost is minimized subject to the constraint imposed by the production function. The solution gives the conditional demand for ore and numeraire inputs. These optimized input volumes (represented by $x_o^*(x_i), x_{n,i}^*(x_i), i = 1, 2$) are then used to calculate the firm's expenditure at equilibrium. This represents the lowest possible cost for any given level of metal demand which is exogenously given. Finally, the total optimized cost (TC) is divided by the equilibrium level of ore processed (x_o^*) to characterize the *total average costs* of the firm per ore processed where $AC = TC/x_o^*$.

Figure 1 presents the approach used for the theoretical model, which starts with the firm's objective of minimizing costs. From this we derive conditional ore demand, which is then used to calculate the firm's optimized total average cost, which reflects average cost per ore after making the most economical input decision.

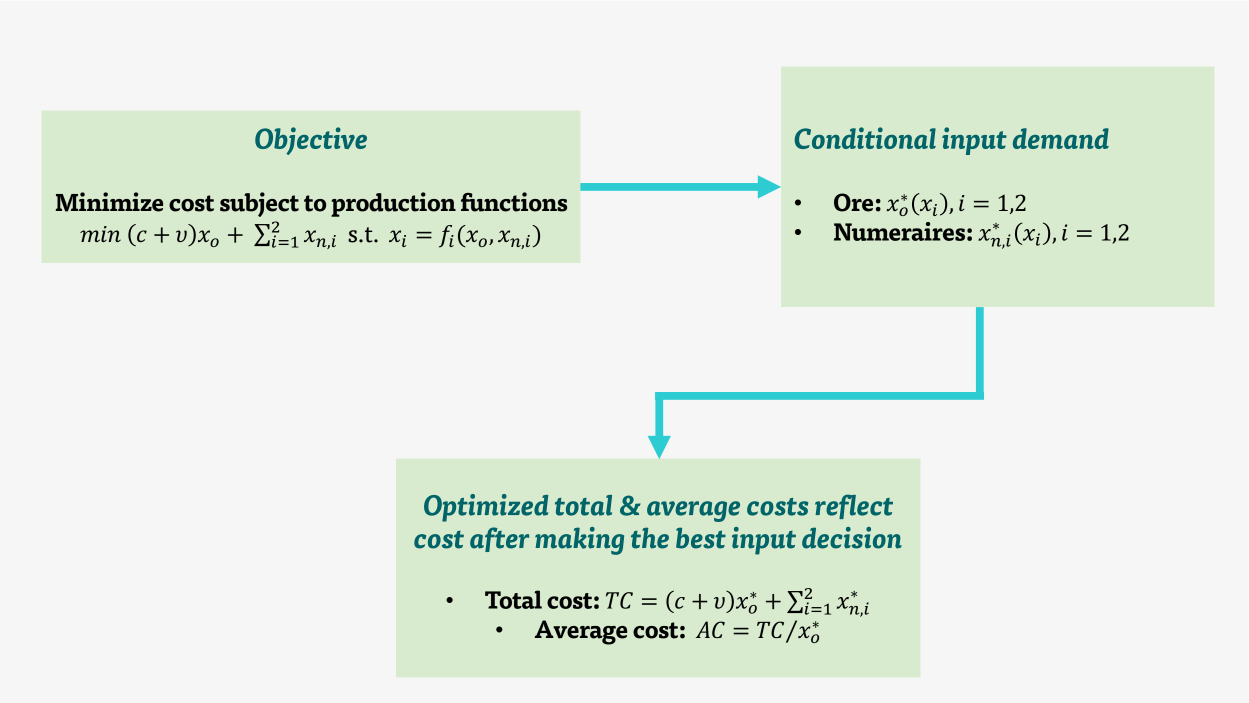

Figure 1: Theoretical framework

3 Characterization of Average Costs for Single and Joint Producers

In this section, we solve for the optimized total average cost of the firm producing a single metal versus that of a firm producing two metals via its joint production technology. Characterization of average costs is important for metal production decisions because it has direct implications for the economic feasibility or profitability of companies involved in the extraction and processing of ores. The total average cost (AC) calculated in this section reflects the most economical input decisions made by the firm. Thus, it provides insights on how firms engaged in the production of metals (either as single/individual or joint metals) can better manage their resources, optimize their costs, and improve their profitability.

3.1 Single metal production

For a single metal producer, the solution is solved from the following constrained optimization problem using the Lagrangian method:

$$L(x_o, x_{n,1}, \lambda_1) = (c+\nu)x_o + x_{n,1} + \lambda_1[x_1 - f_1(x_o, x_{n,1})]] \tag{1}$$

The conditional demand for ore and numeraire input are calculated from the following first order conditions:

$$\frac{\partial L}{\partial x_o} = c + \nu - \lambda_1 \frac{dx_1}{dx_o} = 0 \tag{2}$$

$$\frac{\partial L}{\partial x_{n,1}} = 1 - \lambda_1 \frac{dx_1}{dx_{n,1}} = 0 \tag{3}$$

$$\frac{\partial L}{\partial \lambda_1} = x_1 - f_1(.) = 0 \tag{4}$$

$$\tag{5}$$

The solution gives the conditional demand for ore, $x_o^*(x_1)$, and numeraire input, $x_{n,1}^*(x_1)$. The conditional input demands are inserted into the firm's expenditure function to solve for minimized total and average costs as follows:

$$x_o^* = [\frac{(x_1/A_1)\epsilon_1^{\beta}}{(c+\nu)^{\beta}}]^{1/(\alpha+\beta)} \tag{6}$$

$$x_{n,1}^* = \frac{(c+\nu)x_o^*}{\epsilon_1} \tag{7}$$

$$TC_{single} = \frac{(c+\nu)x_o^*(1+\epsilon_1)}{\epsilon_1} \tag{8}$$

$$AC_{single} = \frac{TC}{x_o^*} = \frac{(c+\nu)(1+\epsilon_1)}{\epsilon_1} \tag{9}$$

We find that the optimized total cost of the single metal producer per unit of ore treated (AC_{single}) increases with c (per unit cost of extracting and processing ore) and ν (per unit tax paid per ore processed). These two parameters are cost increasing (c, ν). In addition, we find that a higher ϵ_1 (e.g., high grade ore or high concentration rates) leads to decreases in AC. This is due to the fact that a higher output elasticity of producing metal x_1 by processing the ore (that is, α) increases ϵ_1 which in turn reduces AC_{single}. This is because when the ore is efficiently transformed into metal, average costs decline, indicating the role of output elasticities to ore in affecting the firm's minimum average cost. The solutions also suggest that demand for metal (x_1), the volume of ore processed (x_o^*), and the total factor productivity (A_1), do not affect the single metal producer's average costs per ton of processed ore (AC_{single}).

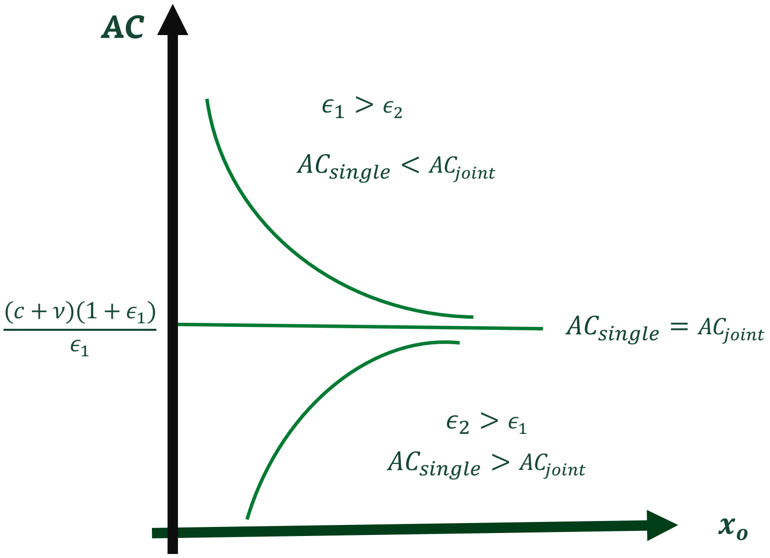

Figure 2: Average cost of single and joint metal producers

Proposition 3.1. ***Single Metal Production***: *The average cost of a single metal producer calculated as optimized total cost per unit of ore processed: (i) increases with mining and processing per unit costs, c, and tax rate per unit of ore, ν, (ii) declines with a relatively higher output elasticity of ore, compared to the output elasticity of the numeraire input, ϵ_1, but (iii) does not change with the total factor productivity of the plant (A_1), the volume of ore processed (x_o^*), and the exogenously given metal demand (x_1).*

3.2 Joint metal production

For joint metal producers (x_1, x_2), the firm's objective to minimize expenditure subject to production functions is given as follows, where $i = 1, 2$.

$$L(x_o, x_{n,i}, \lambda_1, \lambda_2) = (c + \nu)x_o + x_{n,1} + x_{n,2} + \lambda_1[x_1 - f_1(x_o, x_{n,1})] + \lambda_2[x_2 - f_2(x_o, x_{n,2})] \quad (10)$$

The solution is solved from the following first order conditions:

$$\frac{\partial L}{\partial x_o} = c + \nu - \lambda_1 \frac{dx_1}{dx_o} - \lambda_2 \frac{dx_2}{dx_o} = 0 \quad (11)$$

$$\frac{\partial L}{\partial x_{n,1}} = 1 - \lambda_1 \frac{dx_1}{dx_{n,1}} = 0 \quad (12)$$

$$\frac{\partial L}{\partial x_{n,2}} = 1 - \lambda_2 \frac{dx_2}{dx_{n,2}} = 0 \quad (13)$$

$$\frac{\partial L}{\partial \lambda_1} = x_1 - f_1(.) = 0 \quad (14)$$

$$\frac{\partial L}{\partial \lambda_2} = x_2 - f_2(.) = 0 \quad (15)$$

The solutions are solved from the following non-linear expressions:

$$x_o^*(c + \nu) = \frac{\epsilon_1[x_1/A_1]^{1/\beta}}{x_o^{*\epsilon_1}} + \frac{\epsilon_2[x_2/A_2]^{1/\eta}}{x_o^{*\epsilon_2}} \quad (16)$$

$$x_{n,1}^* = \frac{(x_1/A_1)^{1/\beta}}{x_o^{*\epsilon_1}} \quad (17)$$

$$x_{n,2}^* = \frac{(x_2/A_2)^{1/\eta}}{x_o^{*\epsilon_2}} \quad (18)$$

$$TC_{joint} = (c + \nu)x_o^* + \frac{(x_1/A_1)^{1/\beta}}{x_o^{*\epsilon_1}} + \frac{(x_1/A_1)^{1/\beta}}{x_o^{*\epsilon_1}} \quad (19)$$

$$AC_{joint} = \frac{(c + \nu)(1 + \epsilon_1)}{\epsilon_1} + \frac{(\epsilon_1 - \epsilon_2)(x_2/A_2)^{1/\eta}}{\epsilon_1 x_o^{*(\epsilon_2+1)}} \quad (20)$$

First, we find that the parameters c and ν affect the average optimized cost of the joint producer represented by AC_{joint}, directly through the effects of increasing the per unit cost of processing ore and indirectly through the effect of changing the volume of ore processed (x_o^*). Overall, a higher c, ν leads to a higher AC_{joint} for each volume of ore processed. Second, we find that AC_{joint} is affected by the volume of ore processed (x_o^*), while AC_{single} is not, as presented in Figure 2. The figure suggests that if $\epsilon_1 > \epsilon_2$, then increases in ore processed reduce average cost of the joint producer, while, if $\epsilon_1 < \epsilon_2$, then increases in ore processed raise the average cost of the joint producer. If $\epsilon_1 = \epsilon_2$, then $AC_{single} = AC_{joint}$.

Related to this, Figure 2 also illustrates that, if $\epsilon_1 > \epsilon_2$, then $AC_{single} < AC_{joint}$, and vice versa. This means that joint metal producers are able to enjoy lower average costs than single metal producers only if the additional metal jointly produced (x_2) has a higher relative output elasticity with respect to the ore than the first metal. For example, instead of processing ore to produce only copper as an individual metal (x_1), the joint producer can reduce its average cost by processing ore to produce both copper and cobalt as joint products, if $\epsilon_2 > \epsilon_1$. This highlights the need to use advanced technologies (e.g., enhanced grinding and crushing, advanced hydrometallurgy, etc.) to improve the output elasticity of producing critical metals, in particular those with lower concentration rates.

In addition, the model suggests interesting findings related to scenarios where a base metal, such as copper (x_1), has a well-advanced production technology that is relatively more technically efficient compared to critical metal processing, such as cobalt (x_2). Specifically, when $\epsilon_1 > \epsilon_2$, joint metal producers are able to reduce their average cost (expressed in terms of dollar per ton processed) with the volume of ore processed. Therefore, under this condition, they should increase the volume of ore processed to reduce the average cost.

Finally, we find that metal demand (x_1, x_2), as well as the total factor productivity parameters (A_1, A_2) affect the average cost of ore processing, the direction of which is determined by the relationship between ϵ_1 and ϵ_2. Thus, unlike the single metal producer, the joint metal producer's (non-constant) average costs and ultimately its profitability are affected by a combination of multiple parameters, ranging from metal demand (x_1, x_2), costs

(c, ν), to technical production efficiency parameters $(\epsilon_1, \epsilon_2, \beta, \eta, A_1, A_2)$. On the contrary, the single metal producer's average cost is governed only by three parameters, namely, c, ν, and ϵ_1.

Wrapping up, the model presented in this section illustrates that joint production is likely to result in complex relationships between average cost and exogenous model parameters (metal demand, technical and cost parameters). The combined effect of these parameters governs production decisions and potentially impacts supply chain risks. Overall, the results highlight the importance of the relative output elasticity of the ore (ϵ_i) in governing the response of average costs (AC) to changing model parameters, such as unit costs (c) and taxes (ν), total factor productivity (A_i), metal demand (x_i), and the volume of the ore processed (x_o), when metals are produced jointly. On the contrary, when metals are produced as single products, the response of AC to model parameters (c, ν, ϵ_1) is less complex and more direct.

Proposition 3.2. ***Joint Metal Production***: *(i) The average cost of a joint metal producer, calculated as optimized total costs per unit of ore, varies with changing cost parameters (c, ν), metal demand (x_1, x_2), volume of ore processed (x_o^*), and total factor productivity (A_1, A_2). The direction of change is governed by the relationship between the output elasticities of ore for the two metals (ϵ_1, ϵ_2). (ii) If $\epsilon_1 > \epsilon_2$, joint metal producers can reduce their total average cost to approach that of a single metal producer, by processing more volumes of ore, keeping other factors constant.*

Proposition 3.3. ***Comparing Single with Joint Metal Production***: *(i) The average cost of a metal producer, calculated as optimized total costs per unit of ore treated, is higher for joint producers of metals than single producers of metals $(AC_{joint} > AC_{single})$, if $\epsilon_1 > \epsilon_2$, and vice versa. (ii) For a single metal producer, average costs are constant for changing volumes of ore processed. Instead, for a joint metal producer, average costs could be increasing, declining or be constant with changing volumes of ore, depending on the relationship between the output elasticities of ore for the two metals (ϵ_i).*

The results presented in this section suggest that there are certain conditions under which joint metal production could offer cost savings compared to single metal production. First, when single metal producers consider switching to a joint production system, their average cost per ore could decline (for each volume of ore processed) if the second jointly produced metal has a higher relative output elasticity of ore (e.g., more advanced metal refining processes) than the initial metal. In this scenario, switching from single to joint production, offers cost savings. However, if this condition does not hold (i.e., the relative output elasticity of the second jointly produced metal is lower), then increasing the volume of ore processed could lower AC. In this latter case, with increasing x_o, the AC_{joint} will decline and approach AC_{single}, making the switch from single to joint cost-effective.

4 Single versus Joint Production of Copper, Cobalt and Nickel: A Case Study

In this section, we use real-world data on mining projects to compare the average costs of operation for single and joint metal producers across the globe. Insights from the theoretical model are used to interpret trends and patterns in the data. The analysis is based on a subset of metals that are considered essential for the energy transition (Fikru and Kilinc-Ata, 2024) and that can be produced jointly: copper, cobalt, and nickel.

In section 4.1 we present the sample based on which empirical analysis is performed. Section 4.2 then provides a discussion of the different components of AC_{single} and AC_{joint}, which capture costs at both the mining and refining stages, as well as the cost of several numeraire inputs. Related to this, a correlation analysis is performed to identify strong/weak correlations among the different cost components, and correlations between AC and x_o^*. In section 4.3, we perform equality of mean tests to determine whether the sample of observations captured in our data align with $AC_{single} > AC_{joint}$, $AC_{single} < AC_{joint}$, or $AC_{single} = AC_{joint}$ as presented in the model results from Figure 2. Finally, in section 4.4, we show country rankings to identify those geographies where the cost of mineral extraction and metal processing per unit of ore processed is higher or lower for single versus joint producers.

4.1 Data source and sample characteristics

We obtain data on the average cost of ore processing (AC) from our institutional subscription of the S&P Global Market Intelligence. The analysis is based on cross sectional data from the year 2022 where the unit of analysis is a mining operation or project.[1] We select mines that produce copper (Cu), cobalt (Co), and/or nickel (Ni) for our case study. S&P provides the cash cost flow breakdown at the mine operation level. The data presents the total cash cost as a ratio of total ore processed or treated at each mining site, in dollars per ton. Total cash cost includes the mine site cost (direct mining and milling cost), the transport and offsite costs, as well as the smelting and refining costs.

Thus, this variable serves as a proxy for our definition of average cost, $AC = TC/x_o^*$.[2] The data further decomposes this value into the following six cost components, all measured in dollars per tonne of ore: (1) royalty and production taxes (for brevity's sake, *royalty*), (2) transportation/shipment cost, treatment and refining charges (for brevity's sake, TTR), (3) labor cost, i.e., wages attributable to mining and processing (for brevity's sake, *labor*), (4) energy cost, i.e., petrochemical fuel for heavy off-road and light vehicle uses, mine and mill power costs, including grid and own-power petrochemical generation for electrical equipment (for brevity's sake, *energy*), (5) reagents cost, i.e., at the mill level: chemicals, including acids, leach agents, flotation and agglomeration agents, flocculants, pH balancers (for brevity's sake, *reagents*, and (6) all other costs for the mining operation (e.g., explosives cost at the mine

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[1] For example, the Eagle mine operation in the US is 100% owned by Lunding Mining Corporation and produces copper, cobalt and nickel. Morenci SX-EW is also located in the US but produces just copper, and its ownership shares are as follows: Freeport-McMoRan Inc. (72%), Sumitomo Metal Mining Co. Ltd. (25%), and Sumitomo Corp. (3%).

[2] Since the mining sites in our sample have already processed the given ore, we consider the volume of ore processed to be consistent with cost minimization goals.

level, grinding media and activated carbon at the mill level, third party site services such as geological services, etc), (for brevity's sake, *other onsite*).

For 2022, for the selected metals (Cu, Co, Ni), data is available for a total of 427 mining projects across the globe. Among this sample, a total of 62 mining sites are joint producers as follows: 12 Co-Cu, 14 Co-Ni, 18 Cu-Ni, and another 18 Co-Cu-Ni. The remaining 365 mining sites are single metal producers. Among the 427 observations in our sample, 21 are located in Canada and 25 in the US. Table A1 in the Appendix presents the number of mining projects included in our sample, filtered by the three given metals and differentiating between joint and single production types. The number of observations per metal is unbalanced towards copper projects. For example, out of the 365 single extraction projects at the global level, 343 produce copper, 18 nickel and 4 cobalt. In parallel, in North America (defined as US and Canada), 38 projects extract copper, only one produces nickel, and none produces cobalt. Looking at the 62 joint producers, the numbers are more balanced at the global level, but significantly decrease at the North American level, with 5 projects producing Co-Cu-Ni, one project Co-Cu, and another one Cu-Ni. For this reason related to the sample size, in all the analyses focused on North America, we make a comparison between single and joint producers, without delving into the exact metal produced.

Figure 3 presents the country rankings based on average cost per ore (AC) at the mining site level using all observations in our sample. AC is measured as dollars per tonne of ore processed and is plotted on the primary y-axis. The secondary y-axis presents the volume of ore processed per site in kilo tonnes (x_o^*). This figure suggests that average costs and ore processed vary significantly along the 427 mining sites located in a total of 46 countries. Not surprisingly, those countries extracting more metals tend to have lower average costs. Please refer to Table A1 in the Appendix for the number of mining projects for each country.

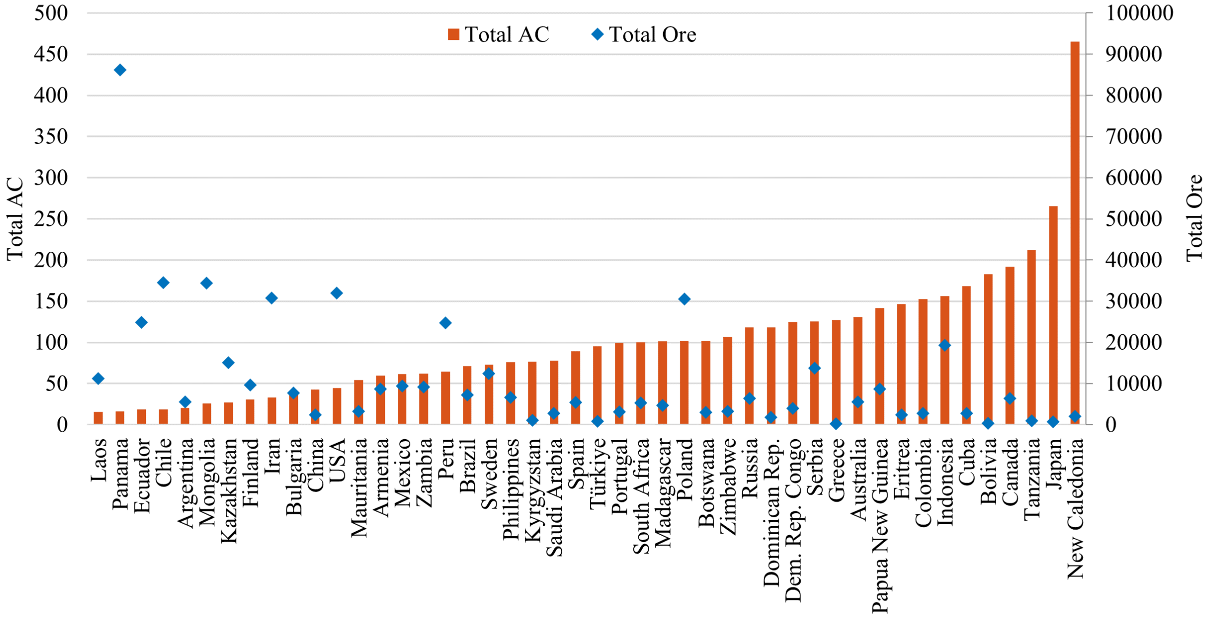


Figure 3: Mining project locations ranked according to average cost (left axis, \$/*tonne*) and average ore (right axis, *kilotonnes*) at the mine site level (N=427).

4.2 Components of average cost of mining and refining

This section presents a comparative exploration of the average cost of ore processed for the two types of extraction and processing sites in our sample (365 single and 62 joint metal producers). We further categorize these observations into those doing single production of just Co, just Cu, and just Ni; and those doing joint extraction as follows: Co-Cu, Co-Ni, Cu-Ni, Co-Cu-Ni.

Figure 4, by analyzing all observations at the global level ($N = 427$), suggests that there are differences between single producers and between joint producers in their cost make-up, volume of ore processed, and total average costs. These differences are essentially driven by the type of metal extracted. For example, reagent costs are more relevant for joint producers of Co-Cu and Co-Ni than for joint producers of Cu-Ni and Co-Cu-Ni. Moreover, copper production has the lowest average cost per ore, while the production of nickel alone exhibits the highest average cost, illustrating that even among single metal producers costs can vary, possibly due to differences in output elasticities of ores. Interestingly, the production of nickel both as single and joint product (in Co-Ni and Co-Cu-Ni) displays the highest per site average cost, possibly due low output elasticities, the high onsite cost of mining (e.g., use of explosives), and the expensive refining procedures (e.g., high pressure acid leaching). Finally, it is important to point out that, among the sample, copper presents a much higher per-site volume of ore processed. This could likely be due to the higher availability of advanced ore processing technologies that cost-efficiently refine copper metal.

Figure 5 presents the same data for mining sites located in the US ($N = 25$) and Canada ($N = 21$). In North America, copper still presents high ore levels and low production costs. There are however some important differences. First, no site produces Co nor Co-Ni. Secondly, the cost of reagents accounts for a very small share of overall costs. Finally, royalty costs affect nickel and Co-Cu more than others, while labor costs are especially important for Cu-Ni joint production.

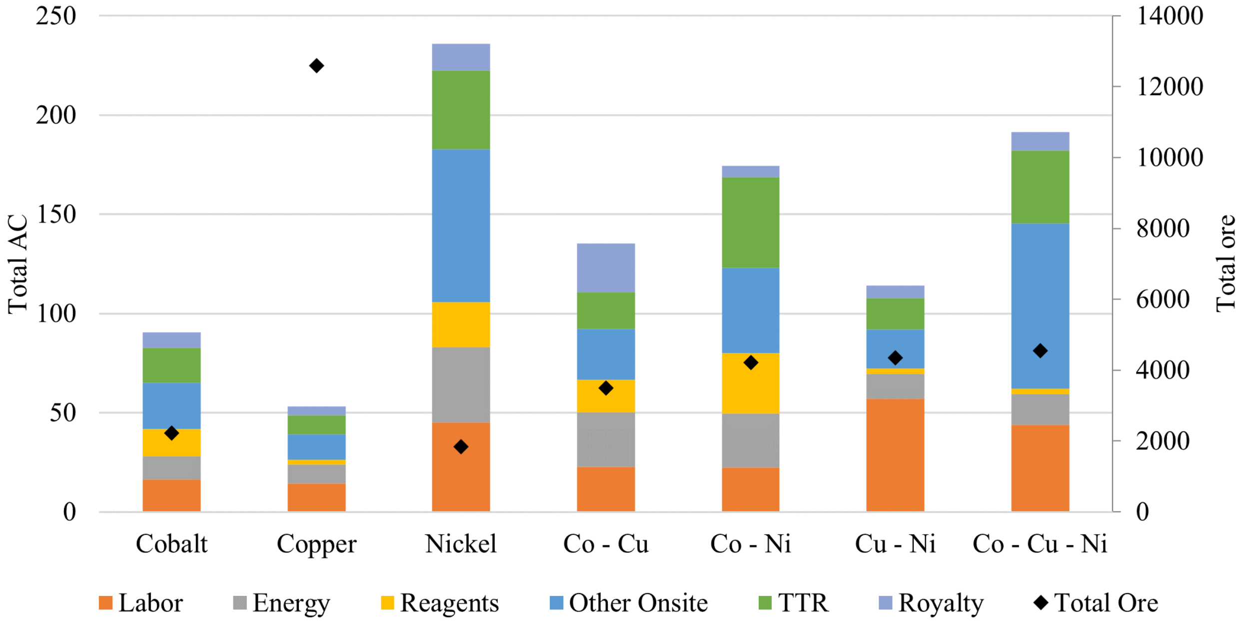


Figure 4: Average costs and components (left axis, $\$/tonne$) and average ore (right axis, $kilotonnes$) (N=427).

Since the dataset allows the decomposition of the average cost of ore processing (AC) into six different components, one could examine the relationship between these categories

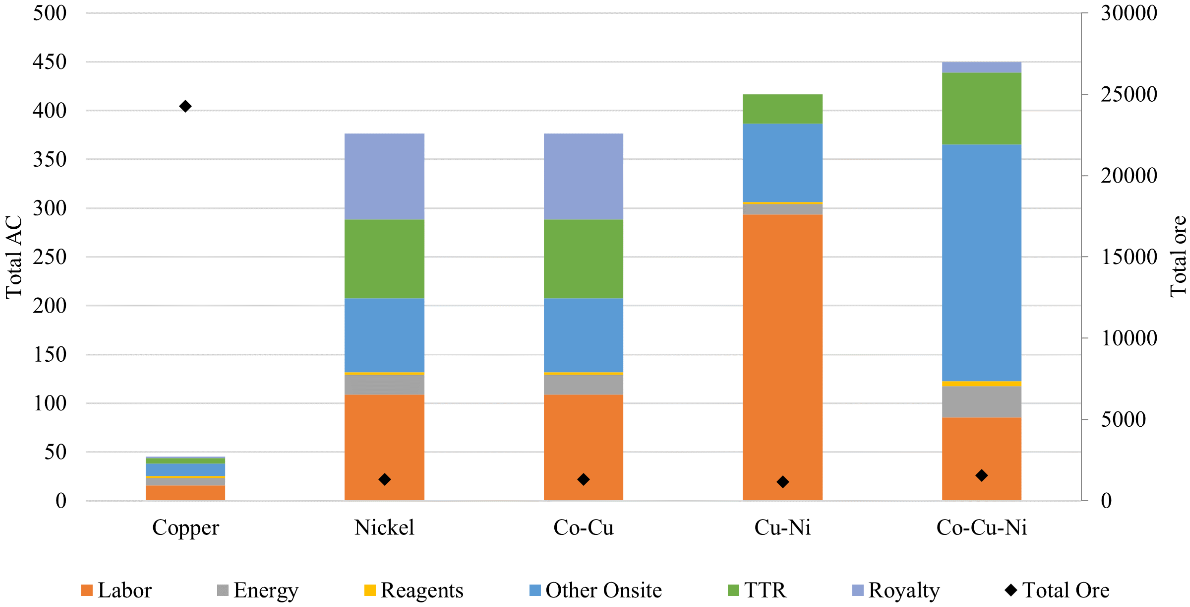
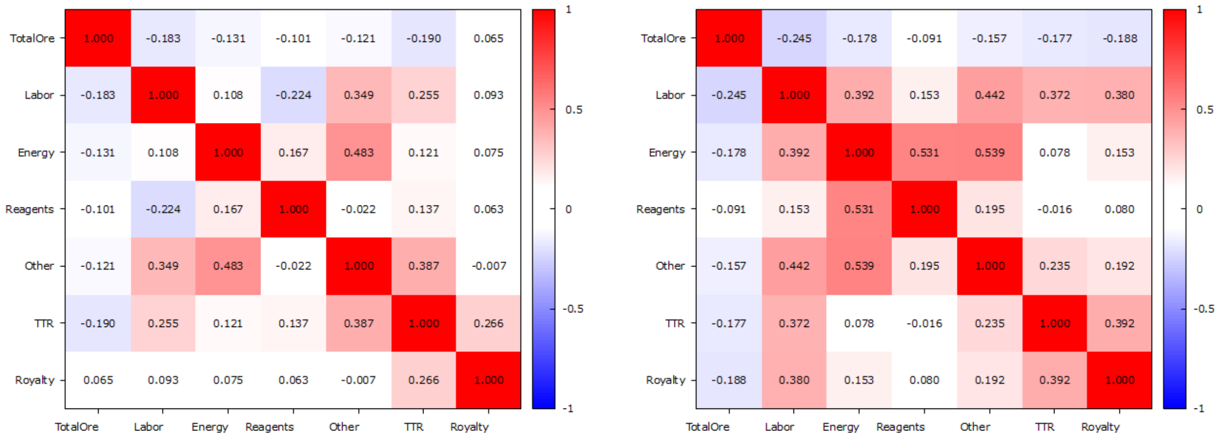


Figure 5: Average costs and components (left axis, $\$/tonne$) and average ore (right axis, $kilotonnes$) for North America (US and Canada) only (N=46).

and the volume of ore processed. Figure 6 presents correlation matrices (Pearson's product-moment correlation) among the average ore extracted and the six different cost components, for joint producers (6a) and single producers (6b), at the global level. The correlation coefficients of the different cost components vary significantly across joint versus single metal producers. For example, among single metal producers, there is a negative correlation between the ore extracted and all six costs, especially labor costs (-0.245), and positive correlation among almost all costs categories, especially between energy and reagents (0.531) and energy and other onsite costs (0.539). On the other hand, for joint producers, transport, treatment and refining charges (TTR) have the strongest negative correlation with the average ore extracted (-0.190) and the various cost items are loosely correlated with each other, except for energy and other onsite costs (0.483).

Figure 7 replicates the same correlation analysis for the US and Canada. It is possible to observe similarities in some trends, despite the smaller sample. Overall, we find there are differences between joint (7a) and single (7b) metal producers. Similar to the global



	TotalOre	Labor	Energy	Reagents	Other	TTR	Royalty
TotalOre	1.000	-0.183	-0.131	-0.101	-0.121	-0.190	0.065
Labor	-0.183	1.000	0.108	-0.224	0.349	0.255	0.093
Energy	-0.131	0.108	1.000	0.167	0.483	0.121	0.075
Reagents	-0.101	-0.224	0.167	1.000	-0.022	0.137	0.063
Other	-0.121	0.349	0.483	-0.022	1.000	0.387	-0.007
TTR	-0.190	0.255	0.121	0.137	0.387	1.000	0.266
Royalty	0.065	0.093	0.075	0.063	-0.007	0.266	1.000

(a) Joint producers (N=62).

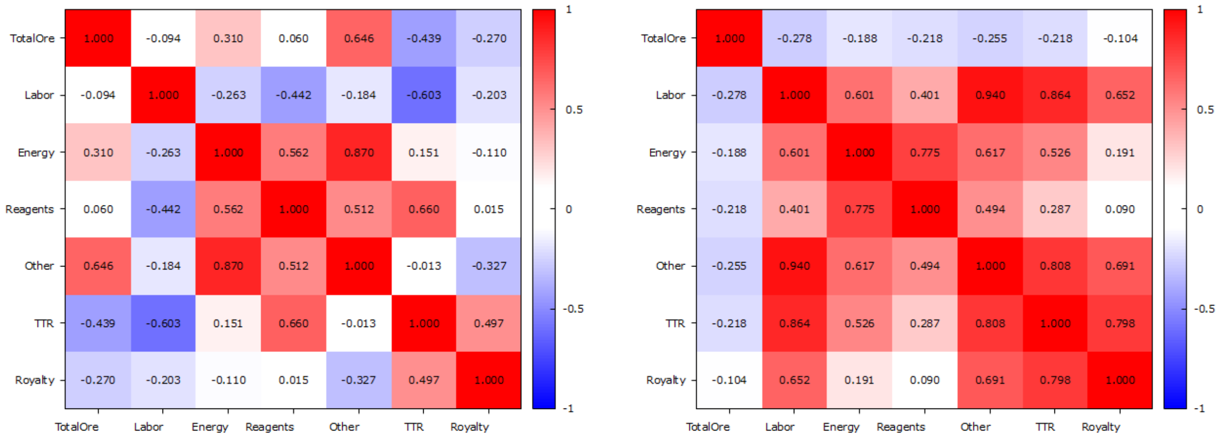
	TotalOre	Labor	Energy	Reagents	Other	TTR	Royalty
TotalOre	1.000	-0.245	-0.178	-0.091	-0.157	-0.177	-0.188
Labor	-0.245	1.000	0.392	0.153	0.442	0.372	0.380
Energy	-0.178	0.392	1.000	0.531	0.539	0.078	0.153
Reagents	-0.091	0.153	0.531	1.000	0.195	-0.016	0.080
Other	-0.157	0.442	0.539	0.195	1.000	0.235	0.192
TTR	-0.177	0.372	0.078	-0.016	0.235	1.000	0.392
Royalty	-0.188	0.380	0.153	0.080	0.192	0.392	1.000

(b) Single producers (N=365).

Figure 6: Heatmap of the correlation matrix between the average ore extracted and the six cost categories, for joint versus single projects, at the global level. The gradient goes from red (+1), to white (0), to blue (−1).

level, North American single metal producers exhibit negative correlations between the ore extracted and all six costs, especially labor costs (-0.278), and positive correlation among each costs categories, especially between labor and other onsite costs (0.940) and labor and TTR (0.864). The ore extraction for joint producers ($N = 7$), is correlated mostly with TTR (-0.439), while the two cost categories most tightly linked with each other are energy and other onsite costs (0.870), similarly to the global analysis.

The correlation analysis underscores the interplay between different cost components and the volume of ore processed. Negative correlations between ore volume and cost components, especially labor, suggest that larger operations could benefit from economies of scale. However, the positive correlations among cost categories, notably between energy and other onsite costs (e.g., high energy use for onsite mining/processing operations), indicate the interconnected nature of mining operations, where increases in one cost component (e.g., more refining needs more energy) often lead to increases in others. Finally, there are notable differences between single (labor cost and x_o) and joint (TTR cost and x_o) producers when one looks at the correlations between cost components and x_o. This implies that production decisions could be more driven by labor costs for single producers while TTR costs could



	TotalOre	Labor	Energy	Reagents	Other	TTR	Royalty
TotalOre	1.000	-0.094	0.310	0.060	0.646	-0.439	-0.270
Labor	-0.094	1.000	-0.263	-0.442	-0.184	-0.603	-0.203
Energy	0.310	-0.263	1.000	0.562	0.870	0.151	-0.110
Reagents	0.060	-0.442	0.562	1.000	0.512	0.660	0.015
Other	0.646	-0.184	0.870	0.512	1.000	-0.013	-0.327
TTR	-0.439	-0.603	0.151	0.660	-0.013	1.000	0.497
Royalty	-0.270	-0.203	-0.110	0.015	-0.327	0.497	1.000

	TotalOre	Labor	Energy	Reagents	Other	TTR	Royalty
TotalOre	1.000	-0.278	-0.188	-0.218	-0.255	-0.218	-0.104
Labor	-0.278	1.000	0.601	0.401	0.940	0.864	0.652
Energy	-0.188	0.601	1.000	0.775	0.617	0.526	0.191
Reagents	-0.218	0.401	0.775	1.000	0.494	0.287	0.090
Other	-0.255	0.940	0.617	0.494	1.000	0.808	0.691
TTR	-0.218	0.864	0.526	0.287	0.808	1.000	0.798
Royalty	-0.104	0.652	0.191	0.090	0.691	0.798	1.000

(a) Joint producers (N=7).

(b) Single producers (N=39).

Figure 7: Heatmap of the correlation matrix between the average ore extracted and the six cost categories, for joint versus single projects, for North America only. The gradient goes from red (+1), to white (0), to blue (-1).

drive decision-making for joint producers.

4.3 Comparing single versus joint producers

To compare the average cost of mining and refining by type of production (single versus joint), we perform equality of mean tests based on the two samples, where the null hypothesis states that the means across the two sample are identical (while assuming unequal variances). The mean differences across the two types of producers (single, joint) that are statistically significant are highlighted in bold, where *** for $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 1 presents the results at the global level for all observations in our sample. All the mean differences across single and joint producers are statistically significant, highlighting that the average cost of mining and refining companies does vary by single versus joint production. Not surprisingly, the highest mean difference value is the average cash cost one (AC). Looking at the individual costs categories, other onsite costs come first, followed by labor and TTR costs. These differences in average costs could be attributed to differences in the relative output elasticity of ore, among other factors. More specifically, the empirical results align with the case where $AC_{joint} > AC_{single}$, possibly attributed to lower relative output elasticities of ore for producing energy transition metals such as cobalt and nickel, than producing copper (e.g., $\epsilon_{Cu} > \epsilon_{Co}, \epsilon_{Cu} > \epsilon_{Ni}$).

Table 1: Equality of means test: Joint versus single producers ($N = 427$).

Cost component	Mean of joint producers (N=62)	Mean of single producers (N=365)	Mean difference
AC	154.262	62.625	**91.638*****
Labor	38.833	15.929	**22.903*****
Energy	19.476	10.857	**8.620*****
Reagents	11.638	3.563	**8.076*****
Other Onsite	44.563	16.139	**28.424****
TTR	29.171	11.217	**17.954*****
Royalty	10.580	4.920	**5.660*****

Table 2 presents the results for the US and Canada. As one might expect, restricting the geographical focus (and thus the sample size) makes the mean differences of costs across single and joint production less statistically significant, since the projects' variety might decrease. Specifically, royalties lose statistical significance. However, differences in the aggregate category of average cash costs (AC) is still statistically significant across the two types of producers. Among the specific cost categories, labor and other onsite costs display the highest mean differences.

Table 2: Equality of means test for North America: Joint versus single producers.

Cost component	Mean of joint producers (N=7)	Mean of single producers (N=39)	Mean difference
AC	434.369	53.611	**380.758*****
Labor	118.463	18.356	**100.107****
Energy	27.189	7.692	**19.496***
Reagents	4.376	2.263	**2.113***
Other Onsite	195.594	13.954	**181.64***
TTR	68.547	7.779	**60.768*****
Royalty	20.203	3.565	16.637

Finally, Table 3 shows the mean differences only, for the equality of means test performed by comparing single and joint extraction for specific metals. As in the North-America-only analysis, restricting the sample size implies lower significance levels overall. More in detail, differences in costs of reagents are statistically significant just for copper jointly produced with cobalt versus copper produced singularly (first column of the table). Also, other onsite costs are weakly significant for joint versus single production of copper (first and second columns of the table). Moreover, we find that joint production of Co-Cu and Co-Cu-Ni exhibits higher AC than single production of copper (Cu). We also find that joint production of Co-Cu-Ni exhibits higher AC than single production of cobalt (Co) illustrating $AC_{single} < AC_{joint}$.

Overall, results from the equality of mean test reveal that joint producers tend to have higher average cost per unit of ore processed. One possible way to enhance cost efficiency could be improving the relative output elasticity of ore via more advanced mineral extraction and refining processes. Targeting cobalt and nickel might improve their relative output elasticities so that it exceeds that of copper production. The empirical finding appears to be consistent with the case where $\epsilon_1 > \epsilon_2$ from Figure 2. Thus, if the subset of mining projects operates according to the model predictions, joint producers could lower their average costs by increasing the volume of ore processed (e.g,. to benefit from economies of scale).

Table 3: Equality of means test for specific metal type: Joint (Co-Cu, Co-Cu-Ni) versus single (Cu, Co) producers. N_j, N_s represent observations for joint and single producers, respectively.

	Mean Differences			
Cost component	Co-Cu vs. Cu ($N_j = 12$, $N_s = 343$)	Co-Cu-Ni vs. Cu ($N_j = 18$, $N_s = 343$)	Co-Cu vs. Co ($N_j = 12$, $N_s = 4$)	Co-Cu-Ni vs. Co ($N_j = 18$, $N_s = 4$)
AC	**82.0245***	**138.213****	44.825	**101.013***
Labor	8.454	**29.543*****	6.447	**27.536*****
Energy	**17.761***	5.983	**15.572****	3.794
Reagents	**14.075****	0.394	2.762	-10.919
Other Onsite	**12.729***	**70.247***	2.231	59.749
TTR	8.922	**27.244*****	1.069	**19.390****
Royalty	**20.085****	4.803	**16.748****	1.467

These results reveal, again, distinct cost dynamics between single and joint metal producers. Globally, single producers generally exhibit lower average costs (AC) compared to joint producers. The most significant cost components contributing to these differences are other onsite and labor costs. Joint producers, particularly those involved in the production of cobalt and nickel with copper, face significantly higher average costs possibly due to the lower relative output elasticities of these metals compared to copper. These higher costs are primarily driven by the complexities and technical challenges associated with processing multiple metals simultaneously.

In North America, the cost differences between single and joint producers remain pronounced, with joint producers incurring in substantially higher average costs than the global average. The results reinforce the notion that joint metal production, while potentially offering synergies and efficiencies in certain contexts, generally involves higher operational costs. The model findings highlight the importance of using advanced ore processing technologies and economies of scale in reducing costs.

4.4 Comparing average costs across mining locations

Another important reason behind cost differences, beyond the type of metal mined and its extraction method, is the mine site location. As shown in Figure 3, average costs vary significantly across different geographies. Therefore, we present a series of statistical analyses at the country level.

Figure 8 presents country rankings for the average cost of processing (AC) and average ore processed (x_o^*), for joint producers ($N = 62$), while Figure 9 presents the same ranking for single metal producers ($N = 365$).

These figures suggest that, overall, countries that rank high in average cost also rank bottom in volume of ore processed, and countries that rank low in average costs have relatively higher volumes of ore processed. Focusing on joint production, in Figure 8, the US and

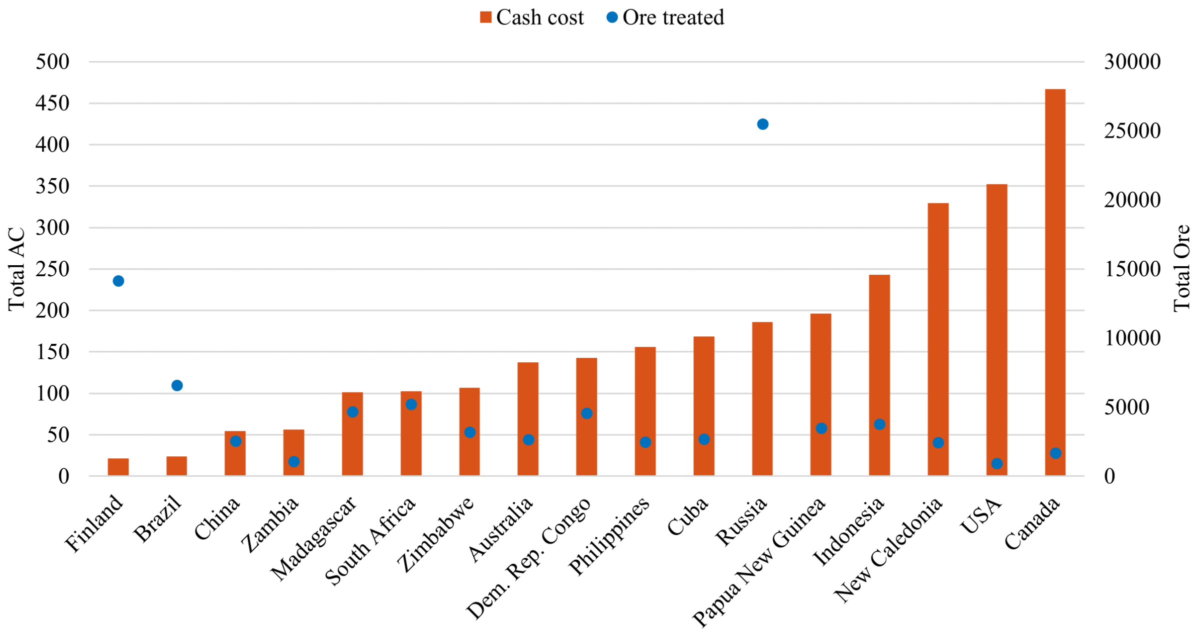


Figure 8: Mining project locations ranked according to average cost (left axis, $\$/tonne$) and average ore (right axis, $kilotonnes$) at the mine site level, for joint producers ($N = 62$).

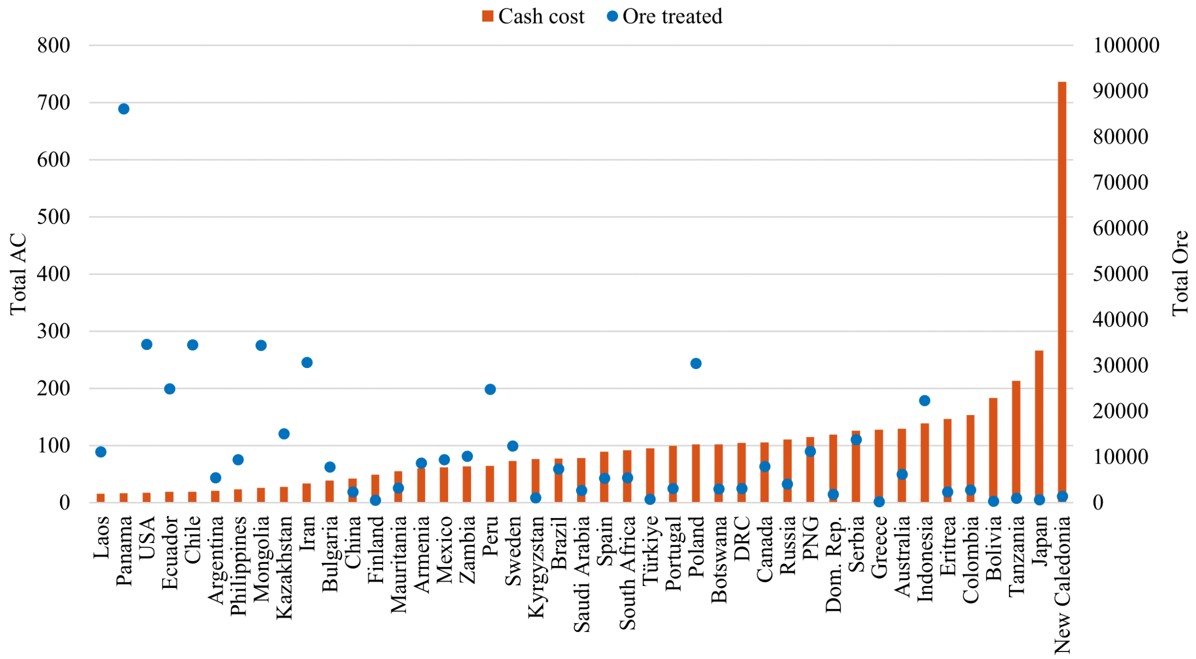


Figure 9: Mining project locations ranked according to average cost (left axis, $\$/tonne$) and average ore (right axis, $kilotonnes$) at the mine site level, for single producers ($N = 365$).

Canada have the highest average cost of processing ore, while, at the same time, positioning themselves among the least producing countries in terms of volumes of ore processed. On the opposite side of the spectrum there is, for example, China, with low average cost and higher production volumes.

Among single metal producers, Figure 9 presents a clearer pattern of the same inversely-proportional relationship between ore extracted (x_o^*) and production costs (AC_{single}). However, this ranking is also influenced by the unbalanced structure of the dataset, i.e., the fact that most projects refers to copper production. For example, the US ranks particularly low in terms of production costs, partly because 100% of its projects ($N = 23$) extract copper, which tends to have lower costs than cobalt and nickel (see Figure 4). On the other hand, New Caledonia, displaying the highest single-production costs, has only one nickel project[3], whose production costs are more than four times those of the average copper producing facility (see Figure 4). For this reason, in Figure 10, we perform the same analysis for cobalt, copper, and nickel individually.

Overall, the data indicates a clear inverse relationship between average processing costs and the volume of ore processed. This pattern is consistent across both joint and single metal producers, although it is more pronounced among the latter due to the predominance of copper projects, which generally incur lower production costs compared to cobalt and nickel. The variability in costs among different countries highlights the importance of considering the specific context of each mining location (e.g., quality or grade of ore processed, regulations and policies governing mining, cost of production, etc.) when analyzing production efficiency. By adopting more efficient and sustainable mining practices and leveraging technological advancements, high-cost regions could potentially increase their production volumes and lower their average costs, thereby contributing to a more balanced and sustainable global supply of critical metals essential for the energy transition.

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[3] The Koniambo nickel mine in New Caledonia, partially owned by the Societe Miniere du Sud Pacifique SA and partially by Glencore PLC, represents an outlier. The site has been unprofitable for more than a decade, due to high operational costs, such as energy and labour, partially because of the remote location. For these reasons, coupled with low nickel prices, the site is currently transitioning into a care and maintenance phase.

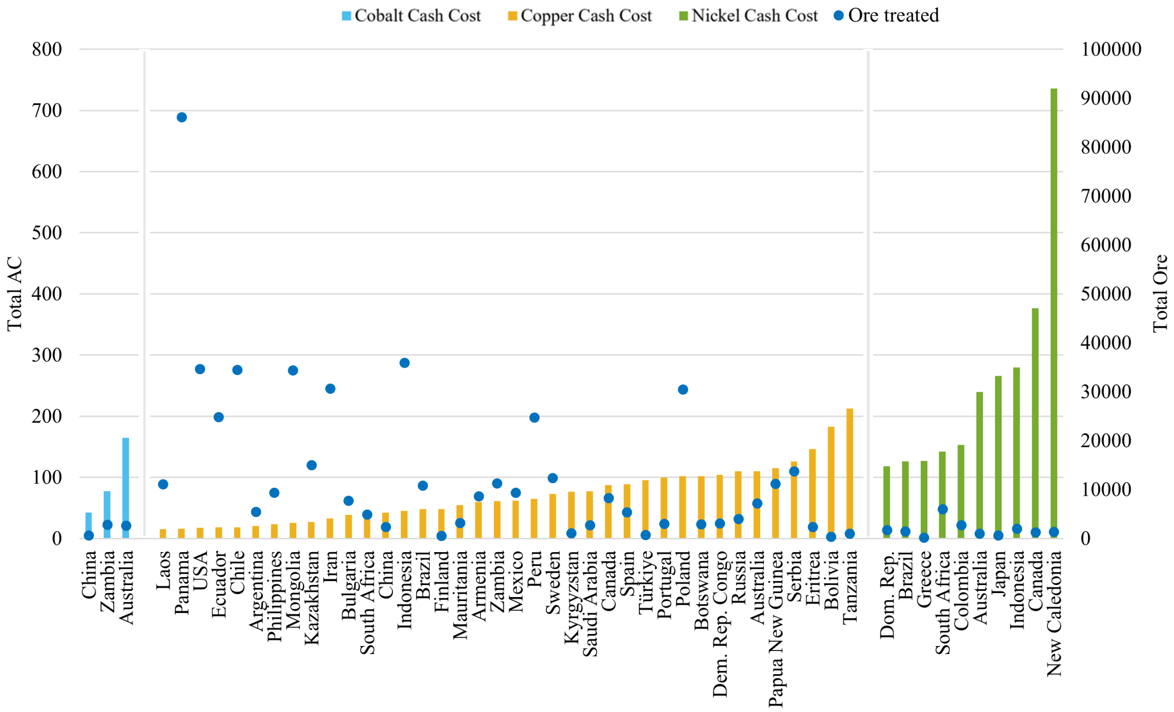

Figure 10: Mining project locations ranked according to average cost (left axis, $\$/tonne$) and average ore (right axis, $kilotonnes$) at the mine site level, for single production only, by metal produced.

5 Conclusion

This study provides a comprehensive framework for evaluating cost efficiencies of mineral extraction and processing using single versus joint production technologies. Understanding cost dynamics is crucial for firms involved in the extraction and processing of ores as an integrated operation. By combining a theoretical optimization economic model with insights gained from 427 mining sites located worldwide, the study presents a comparison of the average cost of processing ore for two types of mining and metallurgical companies: those producing a single energy transition metal in isolation versus those jointly producing more than one energy transition metals by processing the same ore.

The theoretical section presents an optimization approach where the average cost of ore processing is characterized for hypothetical single and joint metal producers. Single metal producers face cost dynamics influenced by per unit mining and processing costs, taxes per unit of ore, and the relative output elasticity of ore. On the other hand, joint metal producers experience more nuanced cost variations tied to changing per unit cost parameters, metal demand, ore volume processed, and total factor productivity. For joint metal producers, the model highlights the role of relative output elasticities in determining production efficiency and average costs, showcasing how higher relative output elasticity of ore can lead to lower average costs.

These findings have significant implications for production decisions, supply chain management, and identifying cost-saving opportunities in the metal extraction industry, particularly for metals critical to the energy transition. First, metal producers can use the insights gained from this study to decide whether and when to adopt single versus joint production strategies based on the relative output elasticities of the ores for different metals. Second, understanding factors that influence average costs can help producers optimize their cost structures. For example, by examining their cost structure, joint producers may adjust the volume of ore processed or invest in technologies that enhance the relative output elasticities of ore.

The empirical section offers a detailed comparative analysis of the average costs of mining and refining operations for single versus joint metal producers of copper, cobalt, and nickel — metals essential for the energy transition. Insights from this analysis show that the average cost of joint producers is significantly higher than that of single producers ($AC_{joint} > AC_{single}$). This highlights the need to design strategies to address the cost challenge faced by joint metal producers. Industry stakeholders shall direct funds and resources towards research and development (R&D) initiatives focused on developing innovative mining and metal refining technologies. In this way they will be able to support the exploration of new methods, equipments, and processes that can enhance efficiency and reduce costs in mining operations. In addition, industry associations can serve as platforms for information sharing, best practice dissemination, and knowledge exchange among mining companies. By sharing such insights, stakeholders can collectively drive improvements in cost efficiency and innovation across the sector. Finally, there is also room for government-sponsored support for innovation and cost efficiency in mining technology, aimed at enhancing the competitiveness and sustainability of the mining sector.

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Appendix

Table A1: Number of mining projects by country and extraction type.

Country	Joint producers				Single producers		
	Co-Cu	Co-Ni	Cu-Ni	Co-Cu-Ni	Co	Cu	Ni
Argentina						1	
Armenia						2	
Australia		4		2	1	19	3
Bolivia						1	
Botswana						1	
Brazil				1		5	3
Bulgaria						4	
Canada	1			4		15	1
Chile						36	
China	2		1	4	1	121	
Colombia							1
Cuba		2					
Dem. Rep. Congo	8					7	
Dominican Rep.							1
Ecuador						1	
Eritrea						1	
Finland		1		1		1	
Greece							1
Indonesia		1				3	2
Iran						1	
Japan							3
Kazakhstan						9	
Kyrgyzstan						1	
Laos						1	
Madagascar		1					
Mauritania						1	
Mexico						21	
Mongolia						2	
New Caledonia		2					1
Panama						1	
Papua New Guinea		1				2	
Peru						22	
Philippines		2				3	
Poland						1	
Portugal						2	
Russia				1		8	
Saudi Arabia						1	
Serbia						2	
South Africa			14	1		2	2
Spain						4	
Sweden						4	
Tanzania						1	
Türkiye						1	
USA			1	1		23	
Zambia	1		1		2	13	
Zimbabwe			1	3			
Total	12	14	18	18	4	343	18

Contact.

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