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Sustainable copper mining: a pathway to emission reduction through renewable energy†

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Due to the importance of copper in battery production, this study was done to determine the environmental impact of copper production, focusing on heap leaching as one of the primary methods to produce copper. To integrate the relevance of sustainable copper mining to batteries, there has been a need to assess other ways to improve the sustainability of copper production. Recently, there has been a shift toward renewable energy resources in the mining industry, especially copper production, but no one has assessed the environmental impacts of this movement. By considering copper production as an example, this study is the first attempt to figure out how this shift can reduce the environmental impacts through life cycle assessment by using SimaPro 9.3 and TRACI 2.1. The results indicated that grid electricity made a significant contribution to stages like electrowinning and ore reduction size (63% or 1.7 tons of total (2.75 tons) CO_2 equivalent). The transition from grid power to wind turbine, solar PV, and geothermal can result in a significant 53%, 38%, and 28% reduction in CO_2 emissions (equals 1,460, 1,046, and 771 kg CO_2 equivalent), respectively. The land use intensity (LUI) values for wind turbines and solar PV were 61.4 and 17.5 m^2 per ton per year.

Environmental significance

The increasing demand for copper, a critical component in batteries, has intensified concerns over its environmental footprint. Conventional copper production, particularly heap leaching, relies heavily on fossil fuel-based electricity, contributing significantly to greenhouse gas emissions. Addressing this issue is crucial for sustainable resource management and reducing the carbon footprints of essential industrial metals. This study presents a Life Cycle Assessment (LCA) of integrating renewable energy sources (solar, wind, geothermal) into copper production. The findings indicate that transitioning to renewable energy can reduce CO_2 emissions by 53%, demonstrating a viable path toward decarbonization in the mining sector. This research provides promising ways for policymakers and industry to promote greener metal extraction processes, leading to reducing the environmental profile of batteries.

1. Introduction

There has been an increasing demand for copper, an essential metal used in modern industries such as batteries and the green tech sectors. In batteries, copper plays a key role in conducting electricity within the battery to ensure the electrons flow during charging and discharging.[1] Due to their remoteness, metals production operations depend on the electricity grid, mainly generated from a mixture of fossil fuels and nuclear power plants, requiring alternative resources that can be used onsite or close to the metals production operations.[2,3] Fossil fuels, such as coal and natural gas, are utilized to generate electricity, leading to greenhouse gases, including CO_x, NO_x, and SO_x, emissions.[4] On the other hand, copper production is projected to increase in order to meet the global demand. Consequently, this increased production will likely lead to significant CO_2 emissions from electricity generation.[5] Igogo *et al.* (2021) reported that Renewable Energy (RE) technologies are the cheapest source of power, making this sector a new and promising source of off-grid sites to be installed even on the mining sites, such as tailing dams.[3]

Although the changing market conditions and business environments in the metals production sector, such as the copper sector, can affect the decision to use RE resources, this trend has gained more attention. Strazzabosco *et al.* (2022)[6] highlighted that only 7% of mining operations in Australia use active or planned RE systems, mostly solar photovoltaic (PV) systems. They also said that 70% of the current renewable resources there have been installed since 2019. Behar *et al.* (2021) provided a database showing the usage of solar projects in the mining sector in Chile.[7] For example, solar PV and thermal are used in El Tesoro, Collahuasi, and Gabriela Mistral with different capacities of 10.5, 25, and 32 MW, respectively. In another study done by Issa *et al.* (2023), it is stated that there has

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been a shift towards the RE in Canada; for example, in Raglan Mine, Cynthia, and Éléonore projects, the types of RE are Wind energy, solar energy, and Geothermal energy, respectively.[8] As a result, it is possible to switch to integrating RE resources, such as solar panels and wind turbines, to reduce the environmental footprint of electricity usage through copper production.[9] However, there are some technical challenges in this way, such as needing sunny or windy conditions or significant designated land, experts, financial, and environmental impacts resulting from RE resources,[8] the latter of which may have long-term consequences. Therefore, a comparative analysis based on the energy source is required to determine what happens if we use renewable resources in copper production. In this capacity, Life Cycle Assessment (LCA) is often employed to evaluate the environmental impacts of each product or process by considering resource consumption and environmental impacts in all stages.[10] While many LCA studies have been conducted to assess the environmental profile of copper production,[11–14] none of them introduced any feasible way to replace the conventional energy resources in the copper sector.

This study is the first attempt to propose a way to determine the feasibility of using renewable resources through cradle-to-gate LCA analysis for copper production *via* a heap leaching process, focusing on the geographical location of North America. In this context, RE sources like solar panels, wind turbines, and geothermal promise to reduce the GHG emissions associated with copper production.[15] As Behar *et al.* (2021)[7] mentioned, both solar photovoltaic and solar thermal technologies can be employed in the mining sector. The former can be used in comminution machines, electro-refineries, and water pumping, and the latter for electricity generation, heat production, thermal leaching, and drying of copper concentrate, respectively. This study tried to assess the opportunities associated with integrating renewable resources into the primary process of producing copper.

2. Methodology

ISO 14040 is a set of international standards developed by the International Organization for Standardization (ISO) that provides guidelines for conducting life cycle assessment (LCA). LCA is a systematic method for evaluating the environmental impacts of a product, process, or activity throughout its entire life cycle, from raw material extraction to disposal. Its principles were employed for this study.[16]

2.1. Methodology transparency and underlying mathematical framework

Like other LCA studies, to ensure transparency and avoid the "black box simulation" issue often associated with life cycle assessment (LCA) software, this study presents the mathematical framework underpinning the numerical calculations conducted by SimaPro 9.3, where the total life cycle inventory (LCI) results are derived using:

$$r = (I^{\mathrm{T}} A^{-1})^{\mathrm{T}} f$$

Here, A is the technology matrix, defining interdependencies between processes, I is the intervention matrix listing environmental flows (*e.g.*, emissions, resource use) per process, f is the functional unit vector (*e.g.*, 1 kg of product), and r is the resulting vector of aggregated environmental interventions. In the next step, these inventory results are then interpreted as potential environmental impacts using TRACI 2.1 characterization factors:

$$\mathrm{Impact}_j = \sum_i (r_i \mathrm{CF}_{i,j})$$

where r_i shows the quantity of environmental flow i, and $\mathrm{CF}_{i,j}$ is the characterization factor for flow i in impact category j (*e.g.*, global warming potential, acidification).[17]

2.2. Goal and scope

As mentioned in the introductory section, an attempt has yet to be made to know how RE sources can contribute to lowering copper production GHS emissions. Therefore, in the first step, this LCA study was carried out to fill the gap and fulfill the previously mentioned goals. In this regard, life cycle assessment was used to estimate how much environmental benefits would be achieved with the utilization of RE sources in the mining sector, focusing on copper production *via* heap leaching. Hence, the first step was to know how much GHG emissions are produced with a conventional electricity grid. Then, various RE sources were considered to know how much contribution they can make to reduce the environmental profile generated by the electricity of copper production *via* heap leaching.

2.2.1. System boundary and functional unit. The data used for performing this LCA study were collected from technical reports on copper production *via* heap leaching in North America.[18–22] The current LCA study was related to all stages utilized in copper production: heap leach feed preparation

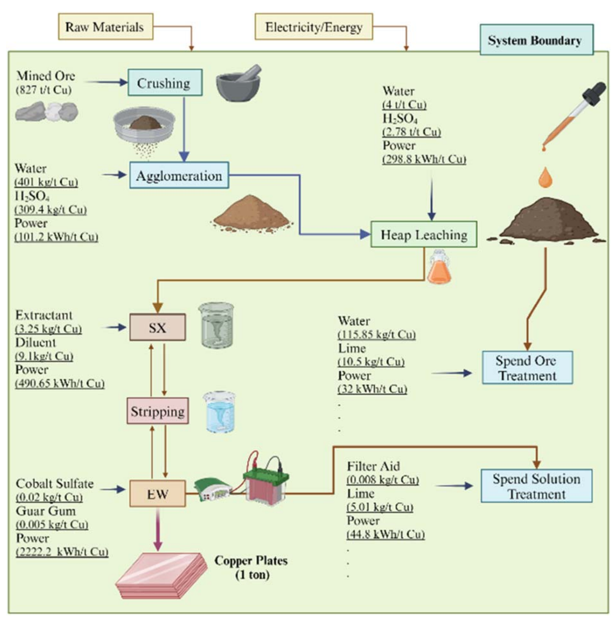

Fig. 1 System boundary for copper production *via* heap leaching.

(HLFP), heap leaching, solvent extraction (SX), and electrowinning (EW) stages (Fig. 1); one metric ton (mt) of copper was assumed as the functional unit.[23]

2.2.2. Copper production *via* heap leaching. Fig. S1† displays the process of producing copper *via* the heap leaching process. In any heap leaching process, the mined ore undergoes a size reduction process using crushers. The crushed oxidic materials are agglomerated in a rotary drum with sulfuric acid and water. The agglomeration is required to create more uniform particles in size and shape, and increase the efficiency of the heap leaching process by streamlining the flow of leaching solution through the heap and removing fine particles contained in the ore that adhere to the coarser particles.[24] Finally, the agglomerated ore is hauled to the heap leach site *via* trucks and stacked by front-end loaders. A grid of pipes (hoses) with drippers is placed over the constructed lifts to apply the leaching solution.[25]

The leaching process is done by applying a mixture of sulfuric acid and water with an optimum acid concentration of 10–15 g l^{-1} and a flow rate of 1–8 l h^{-1}. The heaped ore is irrigated, and the resulting PLS collected *via* the PLS collection system installed under the heap is transferred to the PLS pond.[26] Because the acid reacts with the gangue minerals, adding fresh acid into the raffinate solution discharged from the SX process is necessary.[27] On the other hand, water is added at some points to compensate for the evaporated water.[28] The PLS and raffinate solutions are circulated in a piping system with a few pumping stations and water equipment.[25] Water consumption in this stage results primarily from evaporation, including an estimated 10% loss from heap leach irrigation and additional losses from solution storage. These values are based on the average leaching solution flow rate to the heap leach system.

To separate copper from the PLS, copper ions are extracted and upgraded from a low-grade leach solution into an extractant solvent.[29] There needs to be a database for extractants in the Ecoinvent. However, a surrogate material (benzene) with the same function was used for LIX as a conventional extractant for copper concentration *via* the SX process. The pregnant leach solution (PLS) from the heap leach ponds will be transferred to the SX/EW plant with a PLS flow of up to 681.37 m^3 h^{-1} and PLS feed grade at approximately 3.0 g l^{-1} copper. As the final point of copper production, the upgraded copper solution undergoes the electrowinning (EW) stage, which uses electricity to recover copper from the solution as copper plates.[1]

Two different stages are carried out: the heap closure stage and spent ore treatment, and the spent solution treatment, where various chemicals are used to either neutralize the acidity of the heap/spent solution or remove toxic heavy metals. In this stage, the spent ore is rinsed with alkaline water (pH adjusted with lime). Then, the collected solution was treated to recover copper and remove toxic/heavy metals, and finally, the heap was covered with polymer liners.[25] The collected solution from the SX/EW process is acidic and contains heavy metals and compounds, such as copper, iron, and phosphates, which are dangerous for the ecosystem.[30] Hence, this solution should undergo various steps and processes to eliminate these compounds and increase the pH.[31] Polymer compounds enhance the settlement of (ultra)fine particles formed during neutralization.

Fig. S1.† All data related to copper production were converted into unique impacts on human health and the environment by the developed LCA model. The system boundary showing the process data for this LCA investigation is cradle-to-gate. Fig. 3 displays a system boundary, including air-borne emissions, energy flow, and raw materials to produce one ton of copper from oxide copper ores.

2.3. Life cycle inventory analysis

The inventory analysis was carried out using SimaPro 9.3. Various copper heap leaching processes exhibit differences in the quantity and composition of inputs and outputs. For this study, the primary energy, material inputs, and emissions to process one ton of copper are in Table 1.

All data was gathered from technical reports on copper heap leaching projects performed in North America.[20–22,32] Thus, no assumption was considered. So, for environmental assessment, all processes utilized in copper production must be considered, and the required data related to materials/energy consumption during all phases must be gathered.

As aforementioned, the database for all stages was collected from technical reports and papers related to the PLS recovery system and copper production.[33,34] The corresponding dimension for a commercial heap leaching facility to accommodate 75 million tons of ore was assumed to be 61 m (200 ft) with a leach pad area of 853 745 m^2 in addition to three ponds, including storm, PLS, and raffinate ponds, with an area of 31 840, 18 251, and 16 697 m^2, respectively, to support the heap pad and pond pad materials.

2.4. Impact assessment method

In this study, TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts), developed by the United States Environmental Protection Agency (US EPA), was employed to assess environmental sustainability. For TRACI, the impact categories included are ozone depletion (kg CFC-11 eq.), global warming (kg CO_2 eq.), smog (kg O_3 eq.), acidification (kg SO_2 eq.), eutrophication (kg N eq.), carcinogenics (CTUh), noncarcinogenics (CTUh), respiratory effects (kg PM2.5 eq.), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). In addition, the environmental influences associated with the materials/energy inputs to produce one ton of copper for each stage were evaluated using TRACI.

3. Results and discussion

3.1. Environmental impacts of the HLFP stage

3.1.1. Ore size reduction. The environmental performance of the ore size reduction stage is tabulated in Table S1 and displayed in Fig. S1.† As can be seen, although the conveyor dominated the acidification category, the contribution of the primary and secondary crushers was high in almost all environmental categories. This is related to the high electricity

Table 1 Life cycle inventory of one-ton copper production *via* heap leaching

Input/output	Consumption	Unit
Ore size reduction		
Electricity usage in the crushing stage	148.45	kW h
Conveyor for handling	46.92	Ton km
OAMH		
Conveyor	0.94	tkm
Sulfuric acid	154.7	kg
Electricity	101.20	kW h
Diesel	715.97	MJ
Water	401	kg
Heap leaching stage		
Water	4000	kg
Electricity	298	kW h
Sulfuric acid	910	kg
SX and stripping		
Extractant	3.25	kg
Kerosene	9.1	kg
Electricity	490.65	kW h
Electrowinning		
Copper from the SX	1.07	Ton
Cobalt sulfate	0.02	kg
Guar gum	0.005	kg
Electricity	2222.2	kW h
Spent ore treatment		
Water	115.85	kg
Lime	10.53	kg
Electricity	32	kW h
Flocculant	0.23	kg
Coagulant	0.86	kg
Diesel	733.68	MJ
HDPE liner	4.72	kg
Spent solution treatment		
Lime	5.01	kg
Filter aid	0.008	kg
Electricity	44.80	kW h
Sodium sulfide	0.31	kg
Ferric chloride	0.04	kg
Sodium carbonate	0.080	kg
Extractant	0.025	kg
Diluent	0.070	kg
Coagulant	0.045	kg
Flocculant	0.015	kg
Iron scarp	450.71	kg
Diesel	73.37	kg
Magnesium sulfate	8.12	kg

consumption in these crushers. Furthermore, as ore particle size was reduced, the role of the second crushers in the environmental categories decreased. Previous reports indicate that ore crushing to reduce particle size is one of the stages that consumes a considerable amount of energy in the mineral processing circuits.[35,36]

The prominent contribution of screening in the ore size reduction stage can be explained by considering the number of vibrating screens in the crushing route to prevent oversized pre-particles from entering machines, which requires a remarkable amount of electricity.[37]

3.1.2. Ore agglomeration and materials handling (OAMH) stage. The contribution of each material and energy input to the ore agglomeration stage is presented in Table S2 and Fig. S2.† As expected, diesel dominated all environmental categories, and sulfuric acid and electricity were other contributors with relatively significant environmental impacts. About 7160 MJ (188.4 liters) of diesel to produce one ton of copper was consumed by trucks and leaders to haul and handle agglomerated ore during the OAMH stage.[37,38] The sulfuric acid consumption during agglomeration is due to the addition of this reagent to adsorb fine particles to large particles and create uniform particles in terms of size. Moreover, sulfuric acid is technically employed in the agglomeration step to commence leaching prior to heap leaching and increase the leaching process.[39] Therefore, the environmental impacts associated with this process are allocated to the quantity of sulfuric acid consumed in agglomeration.[40] Compared to diesel, electricity, another primary energy source, has lower environmental impacts. For example, in the eutrophication category, the contribution of electricity was 14%, but for diesel, it was 84%. The electrical grid provides the required electricity for operating various stages in any heap leaching operation; however, the majority of electricity is generated from fossil fuels, producing direct pollution such as carbon oxides (CO_x), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM).[41]

3.2. Environmental impacts of the heap leaching stage

The environmental footprints of material/energy flow in the heap leaching process are mentioned in Table S3 and shown in Fig. S3.† Except for the eutrophication category dominated by electricity, sulfuric acid had remarkable environmental impacts in all environmental categories. It is necessary to add fresh acid to the leach solution due to the sulfuric acid usage for copper extraction from ore.[42,43] The notable environmental role of electricity can be illustrated by its consumption in the pumping system. Various pumping stations are installed around the heap area or ponds to flow the lixiviant in the leaching circuit, transfer PLS, or raffinate from ponds to the plant or *vice versa*.[22]

3.3. Environmental impacts of the SX stage

For the SX stage, a critical stage to upgrade the copper concentration, there are three main chemicals/energy flows for which the environmental impacts were evaluated. The environmental impacts resulting from extractant, diluent, and electricity are presented in Table S4 and Fig. S3.† The environmental results revealed that electricity dominated all environmental categories, resulting from the electricity consumption in the mixer settlers, pumps, filters, and stripping tanks.[44] The organic loss in the SX process is due to the crud (gunk) formation. The crud formation is mainly due to fine particles in the PLS and the settlement of the particles at the bottom of the settler. Despite low extractant consumption in Table 1, its environmental impacts were notable, especially in the ozone depletion, smog, acidification, and fossil fuel depletion categories. This can be related to the extractants' synthesis pathway. Generally, organic chemical synthesis routes are complex, requiring mixing various reagents under specific operational conditions with high energy utilization.[45] As aforementioned, there is no inventory for copper extractant, so another organic material with the same functional group was used. Benzene is a by-product, especially from steam crackers, the production of *p*-xylene, and oil refineries.[46,47] The diluent in the SX process is typically kerosene obtained by fractional distillation of crude oil in an oil refinery. It condenses at an intermediate temperature between diesel fuel and naphtha, and gasoline.[48] Kerosene is manufactured using a highly intensive energy process, and its energy, mainly electricity, potentially relies on fossil fuel consumption. It is reported that about 30% of total energy consumption is in the refining petroleum industry in the US.[49]

3.4. Environmental impacts of the EW stage

During the EW process, cobalt sulfate and guar gum are used to obtain a high-grade copper product in addition to electricity. The environmental profile of each chemical/energy input is tabulated in Table S6.† Intensive electricity (2000 kW h per ton of copper) is applied to provide the required driving force for hydrolysis reactions toward plating copper ions from the solution on the cathodes. Furthermore, another electricity consumption rate is for heating the electrolyte. The main reason for heating the electrolyte is to reduce the resistance of the electrolyte solution and cell, leading to an increased rate of electrodeposition of copper and positively affecting the quality of cathode copper. It is the main reason that electricity dominated all environmental categories (>98%)[50] Other additives, including cobalt sulfate and guar gum, contributed negligibly. Although the cobalt content in the electrolyte is in the range of 160–200 ppm, this negligible amount can reduce anode corrosion.

3.5. Environmental impacts of heap reclamation

The contribution of chemicals and energy flow in the spent ore treatment is displayed in Fig. S5 and Table S7.† As is evident, diesel, followed by HDPE liner, electricity, and lime, dominated all environmental categories. The main reason for the significant environmental impacts of diesel and HDPE liner is related to the fact that the spent ore in the heap should be covered after rinsing, so a layer of HDPE liner is spread and covered with a layer of soil suitable for vegetation. Vehicles, such as trucks and loaders, consume diesel to transport soil and liners. The meaningful environmental impacts of HDPE liners are related to several reasons. The first reason is related to the greenhouse gas emissions of the petrochemical industry for the manufacturing process of this kind of polymer product, involving the extraction and processing of fossil fuels to produce ethylene, an essential component of HDPE liners. The second one is the resource intensity of HDPE production, which requires significant energy and raw materials, such as stabilizers, to enhance resistance or flexibility.

Electricity used in pump stations for water transportation is another contributor to high environmental footprints. The overall environmental footprints of the spent solution treatment are shown in Fig. S7 and reported in Table S7.† In this stage, iron scrap is used to recover copper from the spent solution, which must be used more than the stoichiometric ratio of copper. So, one reason for the significant contribution of iron scrap in this step is its high consumption rate. However, the main reason for the intensive environmental impacts of iron scrap is the energy consumption and emissions during the collection, transportation, processing, sorting, and recycling of iron scrap. For example, iron scrap is required to be sorted before recycling, and the essential processes in this step, which are shredding, shearing, and magnet separation, need intensive electricity.

Electric, diesel, and magnesium sulfate are other contributors with high environmental impacts. The electricity used in solution transportation, thickening, and filtration was about 45 kW h per ton of copper production, leading to the high environmental contribution of electricity in this step.

3.6. Analysis of stage contributions to the overall process

Since copper production *via* heap leaching includes various stages, it was interesting to compare the contribution of each stage to the whole process. As shown in Table S8† and Fig. 2, the contribution of each stage varies across different impact categories. For example, the main contributors were EW, followed by heap SW stages. Also, as expected, the heap leaching step carried greater environmental influence in the acidification and respiratory effects categories, resulting from high sulfuric acid consumption in this step; however, the EW step impacted the eutrophication category owing to intensive electricity usage for making copper electrowon. The results found that a total of 2.7

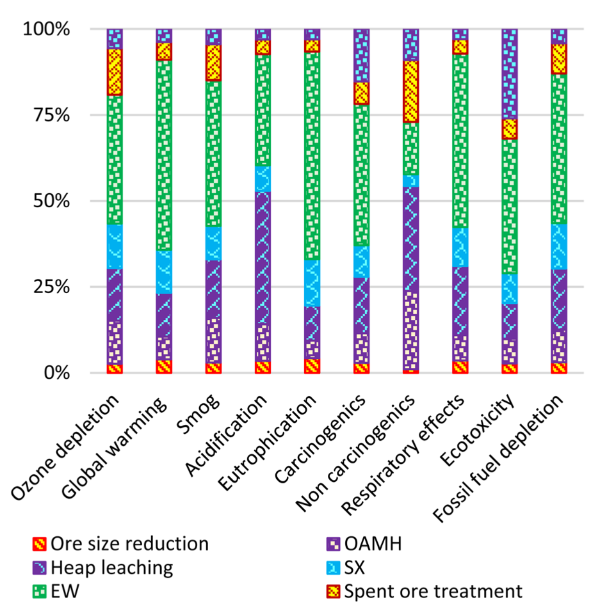

Fig. 2 The contribution of each stage to the whole process of producing one ton of copper.

tons of carbon dioxide and 20.5 kg of SO_2 were generated to produce one ton of copper *via* heap leaching.

4. Sensitivity analysis

A sensitivity analysis was done to measure how electricity consumption contributes to copper production *via* heap leaching compared to other main factors or parameters in the model inputs, shedding light on the study's findings.

This analysis encompassed three scenarios, each involving incremental changes of 1%, 5%, and 10% for three key inputs: electricity (source: grid) and sulfuric acid. The primary objective was to investigate the varying effects of different inputs and parameters on the three primary impact categories under study.

In Fig. 3, electricity consumption plays a crucial role in influencing global warming and eutrophication. For instance, a 10% change in electricity consumption results in a 6.5% impact on global warming and a 7.2% impact on eutrophication. Notably, sulfuric acid consumption exhibits the most significant variation in acidification, with a 10% change leading to a 3.75% variance.

If we analyze the GHG emissions of the electricity used in the entire copper production process (391.3 kg $CO_{2eq.}$ per ton), we see variations in the grid mix across different states. For instance, copper production occurs in states such as Arizona, Michigan, Montana, Nevada, New Mexico, and Utah. These states have different levels of RE in their grid mixes, ranging from Montana with 52% RE to Michigan with only 13%. This variation can significantly impact the environmental footprint, especially considering the substantial contribution of the electrowinning process to overall emissions.

Assuming a shift towards renewables results in a less efficient electricity mix compared to coal-based sources, as shown in Fig. S8,† a 20% change in electricity consumption efficiency could mean notable differences. For example, even if we lose 20% efficiency in Montana (leading to 325 kg CO_{2eq} per ton), this could still result in a 100 kg CO_{2eq} per ton gap compared to a 5% efficiency improvement in Michigan. This highlights the potential environmental benefits of RE adoption despite possible efficiency losses.

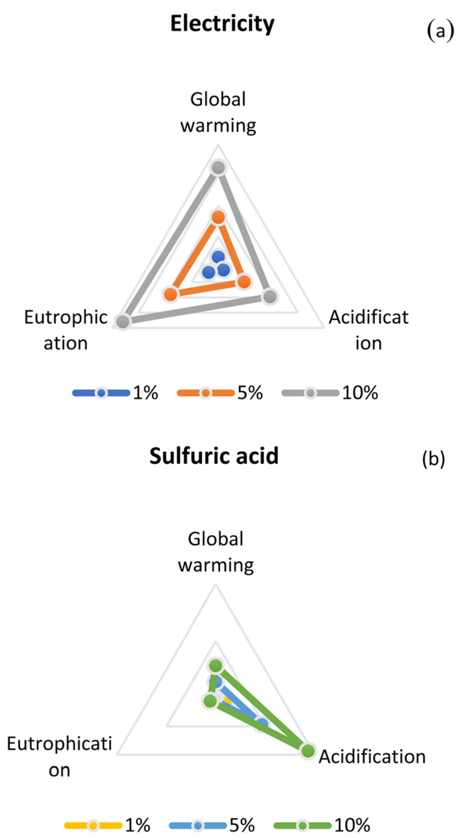

Fig. 3 Comparison of changes in global warming potential, acidification, and eutrophication, (a) electricity (grid), (b) sulfuric acid (1%, 5%, and 10%).

5. Alternative energy supply scenarios

5.1. Environmental assessment of alternative energy supply scenarios

According to the sensitivity analysis part, it was found that a 10% change in electricity consumption results in less (6.5%) CO_2 generation, underscoring the importance of electricity (and its reliance on the specific grid mix) in various impact categories. This finding aligns with the US Department of Energy's Mining Industry Energy Bandwidth Study,[51] which estimates that implementing best practices and research and development (R&D) could lead to significant energy savings and CO_2 emission reductions in mining operations. Additionally, Aydogdu *et al.* (2024) demonstrated that electrifying copper mining haulage systems can substantially decrease CO_2 emissions, highlighting the critical role of electricity consumption in the overall carbon footprint of copper production.[52] Therefore, after approving this idea of electricity's high role in copper production, a comparative analysis was conducted using different power sources: the grid, solar panels, geothermal, and

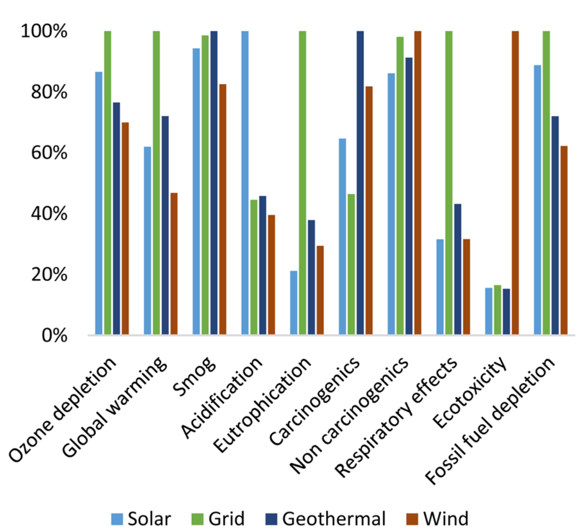

Fig. 4 The comparison of impact categories based on the different power sources.

wind turbines. Fig. 4 illustrates the comparison of impact categories among these four sources. As evident, wind energy stands out as the most environmentally friendly approach to acquiring energy and facilitating copper production through heap leaching methods. Except ecotoxicity and carcinogenics categories, wind turbines had lower environmental impacts, especially in global warming, eutrophication, and respiratory effects, compared to the grid type. Solar PV offered a less sustainable alternative to wind energy, followed by geothermal sources and traditional grids. Transitioning from grid power to wind energy can result in a significant 53% reduction in CO_2 emissions (equals 1459 kg CO_2 equivalent), underscoring the pivotal role of electrical power sources in mitigating the environmental impact of copper production *via* heap leaching.

On the other hand, using solar panels can lead to a 38% (equivalent to 1046 kg of CO_2) reduction in global warming. The impact of the transition from grid to geothermal could decrease CO_2 emissions by 28% (equals 771 kg CO_2 equivalent). The results, depending on location, feasibility, and available facilities, indicate that utilizing these energy sources can substantially reduce copper production. For example, solar thermal process is used in the EW process, which had the highest contribution to environmental categories, or solar PV can be used in all steps.[7]

Another way is to use different scenarios to evaluate the environmental profile resulting from various ratios of electricity generation from solar, wind, and geothermal sources with grid one.

Fig. 5 shows the effect of a mixture of grids with various ratios (20% to 100%) of different sources' usage on global warming. An increase in solar, geothermal, and wind usage decreased CO_2 emissions from electricity consumption in copper production *via* heap leaching. This promising trend suggests that by harnessing the power of solar panels, we can significantly reduce CO_2 emissions in copper production. Despite the lower CO_2 emissions from the grid + wind, this option is not feasible economically and logistically.

The results showed that if mining companies utilize grid + solar panels, copper production will emit less CO_2. For instance, in the scenario of 40–60% grid and solar, 23% less CO_2 generation (700 kg CO_2 per ton of copper) can be achieved.

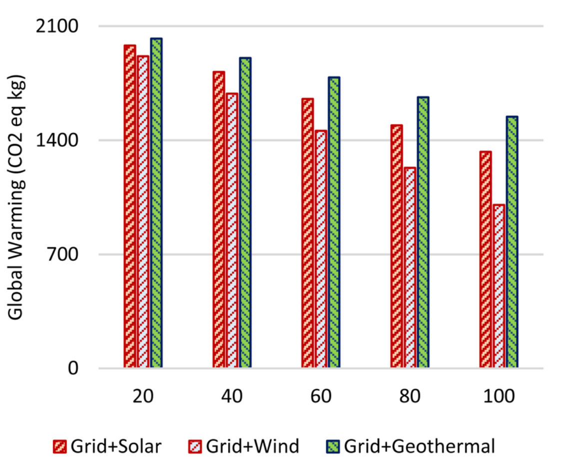

Fig. 5 Global warming results from a grid mixture of solar, wind, and geothermal.

5.1.1. Land use. Land use of RE sources refers to the surface area to build and operate infrastructure to generate electricity from the RE sources.[8] In our case, this term is defined as the surface used to establish wind turbines and solar PV facilities in a mining site, which reduces the environmental profile of copper production. The land use index (DUI) of wind turbines and solar PV was assessed based on the following equation:

$$\text{Land Use Intensity (LUI)} = \frac{\text{RE disturbed area } (\text{m}^2)}{\text{annual production (ton per year)}}$$

So, considering an average annual copper production of 11 000 tons of copper, the LUI values are mentioned in Table S9.† In this calculation, the required electricity demand was assumed to be 8 MW,[22] which could be met using two wind turbines with a generation capacity of 4 MW each.[53] It was reported that the RE sources have higher LUI compared to the fossil fuel energy sources.[8]

5.2. Challenges

It should be considered that any transmission from the grid to two electricity sources, a wind turbine and a geothermal power plant, requires desk studies to make sure they are viable or economically feasible.[52,54] For example, in addition to limited locations suitable for wind turbines, annual maintenance costs are high.[55,56] On the other hand, geothermal energy needs to be built where geothermal reservoirs are located close to the Earth's surface.[52]

Large-scale solar panels can be established where thousands of acres of land are available in almost all mining sites, using hundreds or thousands of solar panels.[57] Furthermore, the maintenance cost for solar panels is far less than the two previous types.[58] Hence, solar panels as an energy source are the best scenario for mining sites. However, it should be noted that, except for the crushing step responsible for most electricity consumption in any mining site, other steps in heap leaching can be operated with a solar panel type.[7] This means that a mixture of grids with solar panels can meet the electricity consumption demand for any heap-leaching process.[3] Moreover, it is essential to reiterate that this mixture has a significant positive environmental impact from copper production *via* heap leaching, providing a ray of hope for a more sustainable future.

6. Conclusion

This study's first attempt was to determine how RE sources can increase the environmental sustainability of copper production, leading to the integration of copper production and battery design. All materials, energy inputs, and emissions were derived from the heap-leaching processes in North America. Simapro 9.1 and Ecoinvent were employed to analyze inventories, and EPA TRACI 2.1 was used for impact assessment.

In the baseline analysis, it was observed that copper production necessitates a substantial amount of energy and the utilization of chemicals, resulting in significant and noteworthy environmental impacts. For example, the overall CO_2 and SO_2 generation to produce one ton of copper *via* heap leaching was 2.75 tons and 20.5 kg, respectively. However, 63% of CO_2 emissions are from electricity consumption, especially in the crusher and EW steps.

Based on the sensitivity analysis, it was found that a 10% reduction in electricity can lead to a reduction in global warming by 6.5%. To reduce the environmental footprints of copper production *via* heap leaching, various sources of electricity generation, including wind turbines, solar panels, and geothermal, were proposed to be used. The global warming generated by copper production was reduced significantly by transmission from the grid to wind, solar panels, and geothermal sources by 53%, 38%, and 28% (equals 1,459, 1,046, and 771 kg CO_2 equivalent), respectively. The land use intensity (LUI) values for wind turbines and solar PV were 61.4 and 17.5 m^2 per ton per year.

To further advance this work, several research avenues are suggested. First, while this study considered individual RE sources, future work should explore hybrid renewable energy configurations (*e.g.*, wind + solar PV, wind + hydropower, solar CSP + geothermal) to assess their combined environmental benefits and operational synergies. Multi-source systems could provide more consistent energy outputs, which is particularly important for mining operations requiring continuous power. Second, dynamic modeling of temporal variations in renewable energy generation (*e.g.*, hourly solar irradiance and wind speeds) should be incorporated into future life cycle assessments to represent real-world operating conditions better. Third, region-specific environmental impacts associated with different renewable deployments, such as water consumption for solar CSP, land disturbance for wind farms, and induced seismicity risks for geothermal plants, should be evaluated to offer more geographically customized sustainability recommendations. Additionally, future studies could assess the feasibility of integrating energy storage systems (*e.g.*, batteries, thermal storage) with renewable generation to overcome intermittency challenges, which are critical for continuous copper production operations. Lastly, economic analysis (LCOE, CAPEX, OPEX) combined with environmental performance would allow for a more comprehensive techno-economic sustainability framework for decarbonizing copper production *via* renewable energy adoption.

In summary, this study highlights the pivotal role that electricity source selection plays in reducing the environmental burdens of copper production and points toward renewable energy integration as a promising pathway for achieving more sustainable mining practices in the future.

Data availability

The data supporting the findings of this study have been included as part of the ESI† file provided with the article. All datasets analyzed or generated during the study can be found within the ESI,† ensuring full transparency and reproducibility of the research. No additional repositories or external databases were utilized for data storage in this study.

Conflicts of interest

There are no conflicts to declare.

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