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Recent Developments in Primary Copper Supply in the United States

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Abstract

Demand for copper is expected to increase in the United States as energy infrastructure expands to accommodate data centers, new electricity generation, and electric vehicles. While scaling-up recycling of copper is important for meeting domestic demand, a number of active and emerging copper producers have announced new activities for expanding primary copper production. Generalized market and facility-level models representing mine energy and materials flows have been developed, but the potential future portfolio of mining supply is diverse and requires further characterization to support planning for supply chains and technology deployment. Herein, we present a dataset of mine projects, providing estimates of copper productivity by technology pathway. We review diesel, electricity, water, and tailing waste generation factors reported in literature and used in life-cycle assessment databases, highlighting incontinences and gaps where values may not represent primary production of copper in the United States, now and in the future. Using data reported between 2021 and 2026, we find 0.9 and 1.6 million tonnes/year of cathode-grade copper production from active and proposed mine projects, respectively. By gathering data from technical reports, we were able to reproduce domestic production reported most recently by the US Geological Survey. We find 21% of new Cu production is explicitly from leaching processes that avoid sending concentrate to offshore smelters. Our findings suggest limits to domestic smelter capacity could be a bottleneck for new projects generating conventional sulphide ore copper concentrate. Partnerships between mines and providers of key resources such as water, fuel, and electricity could have far reaching effects as copper mining expands beyond the Southwest where it holds an established industrial presence.

Keywords: copper, critical materials, pyrometallurgy, hydrometallurgy, tailings, life cycle assessment

Introduction

Copper (Cu) is a transition metal, used in construction, electronics, appliances, medicine, and industry, thanks to its may unique and beneficial properties.[1] It offers high electrical and thermal conductivity, and corrosion resistance at relatively affordable material prices. Copper plays a role in energy system components, specifically wires, cables, circuits, electrodes, catalysts, heat exchangers, fuel cells, and electrolyzers. Annual apparent consumption in the United States (U.S.), reflecting the amount of primary and secondary Cu produced or imported — less exports and changes in Cu stock — has floated around 1.8 million metric tonnes (MMT) of refined Cu since 2010, with 2025 rising to 2.2 MMT (Fig 1a).[2] As of the year 2023, bottom-up projections of Cu demand in the United States reflected "business-as-usual", "green technology", or "dematerialization" scenarios indicate Cu demand rising steadily to between 3-4 MMT by 2050[3] or as high as 6 MMT with expanded EV adoption.[4] Recent expanded plans for data centers and electric vehicles are also reflected in a 2022 S&P projection that suggests demand could spike to 4 MMT as early as 2035. The infrastructure associated with growth in artificial intelligence (AI) supporting data centers alone is expected to increase global Cu demand by 1-2%,[5] while electric vehicle components have grown from negligible to 10% of global Cu demand since 2020. Such rapid projected growth in demand raises questions as to whether new Cu production already in the development pipeline can meet demand.

Derived from ores, Cu is abundant in Earth's crust, with known Cu deposits mined for over 150 years in the U.S. Sulfide ores are processed by milling and floatation of raw ore to concentrate Cu prior to smelting and electrolytic refining to produce cathode grade Cu (99.99 wt.-% Cu). Oxide ores are characterized by lower ore grades, but can be processed through leaching followed by solvent extraction and electrowinning (SX-EW) to produce refined cathode grade Cu (electrowon process). Along with refined Cu imports, these two pathways generate the primary Cu for the U.S. (Fig 1d). Material flows of primary production processes are described by Goonan USGS and reflect the representations often used in literature.[6] Copper is used as an indicator of resource scarcity as a life-cycle impact assessment functional unit, with well-studied linkages between ore grade and resulting increased mine activity per unit product. Ores in the U.S. range in Cu ore grade, but are typically less than 1% Cu content. In 2002, Ayers predicted ore grades would remain below 0.5% post 2000.[7] This has proven to be correct, with the average yield of Cu in ores sent to concentrating processes declining steadily from 0.9% to 0.3% between 1950 and 2020 (Fig 2). Despite this decline, primary domestic production of Cu rose steadily until the year 2000, at which time imports of refined Cu increased sharply (Fig 1a and b). Secondary Cu is produced through the refining of new and old scrap (Fig 2a). Refining of old scrap has remained stable at 175 thousand tonnes per year since 2002, while primary production from domestic ore has decreased. Cu is a recyclable material, reused for centuries and alloyed with zinc and tin for the making of brass and bronze, respectively. The trade of Cu can occur via the distribution of unrefined and refined Cu, as well as ore and scrap, making the tracking of Cu consumption and losses challenging (Fig 1e). Models of stock and flow by Gorman and Dzombak use historical data gathered annually by the USGS[8] to characterize Cu End-of-Life collection and recycling (segment presented in Fig 2e). Table 1 provides definitions of the Cu flows used to report production and consumption statistics.

Increased demand for Cu from energy sectors and pressure to bolster domestic production has encouraged proposals and reactivation of mines for sulfide ore extraction, including greenfield sites such as Pebble Project in Alaska and the Mason Project in Nevada.[9] However, greenfield mines are expected to take more than two decades from prefeasibility and exploration to operation in the U.S., and investments in leveraging waste materials with unrecovered Cu at existing mining sites could become the new face of Cu mining in the U.S. This has been made possible for secondary sulfide ores with bioleaching methods that leverage mesophiles and thermophiles as catalysts to overcome the high activation energy necessary for Cu solvation. High recovery still requires significant flow of raffinate and long project lengths (~3 years per heap pile).[10] Primary sulfide ores (chalcopyrite) require elevated temperatures to avoid passivation and have yet to be leveraged for Cu recovery despite the enormous mass of Cu emplaced in tailings. Holley *et al* estimate the recovery of between 10-50% of copper in wastes is needed to replace US imports of copper product.[11] While tailings recovery is a promising opportunity for expanding domestic production of Cu, we limit our analysis to proposed mine projects that have at least prefeasibility or technical reports publically filed. The focus of this analysis in on primary production from individual mines, while End-of-Life recycling of copper, changes to imports and exports, and policy implications are outside the scope of this study.

While projections of Cu demand have been reported, Cu supply projections are lacking, with no aggregated opensource dataset on active and proposed mine project activities. Herein, we address this gap by developing a geospatial dataset of prominent Cu producing mines and mine projects. We contribute to the evaluation of primary Cu supply by reviewing variables that drive limits on Cu production, such as concentrator capacity and smelting capacity. US Geological Survey (USGS) data dating back to the year 1900 is digitized as part of our data collection, however our primary objective is to contribute new information on mine activity beyond the annual mine capacities reported by the USGS. We review life cycle assessment (LCA) representations of Cu yielding processes and identify research gaps related to energy, water, and waste. The inverse relationship between Cu ore grade, the concentration of metal in ore resource, and energy consumption has been well studied. Yet, energy requirements remain unpredictable at the mine-site level due to variations in ore quality from year to year. This work builds on previous assessments including the Department of Energy Profile of the US Mining Industry for Copper[12] that evaluate both the mine and downstream processing. Our focus is on activities at the mine up through the production of concentrate or the use of SX-EW, and we direct readers to reviews on smelting and refinery processes for further details. With an estimated 54 hard rock metal mining operations in the U.S.,[11] more than 30% primarily generate copper. Characterization of activities at these sites has implications for the resources necessary to advance domestic supply of Cu going forward. The need for data that can support analytical frameworks of materials flows has been identified as a key gap.[13] As Cu supply hold serious consequences for the cost and embodied impacts of energy infrastructure, a review of the state of domestic ore production for Primary Cu production and analysis efforts is impactful and timely.

Table 1. Terminology used to describe key flows and statistics of the copper industry.

Term	Definition	Representation
Rock Moved	Total raw ore containing copper handled at the mine	
Copper Ore Concentrated	Copper content in ore concentrated through milling and flotation	Cu
Copper Ore Grade	The total copper content in the raw ore	%
Gange	The total non-copper content in the ore	
Sulfide Tailings	Waste generated from the mine following ore concentration	
Copper Yield	Recoverable copper from concentrated ore estimated to be extractable. Considered to be the average ore grade sent to milling and flotation.	%
Recoverable Copper	The copper in smelting concentrates, precipitates, and electrowinning	Cu
Refinery Production	The sum of Primary Production and secondary refinery materials	99.99% Cu
Primary Production	The sum of Primary Electrolytic production from domestic and foreign ore and Primary Electrowon.	99.99% Cu
Primary Electrolytic	Refined copper from electrolytic refining of anode copper	99.99% Cu
Primary Electrowon	Refined copper from solvent extraction and electrowinning	99.99% Cu
Secondary	Copper recovered from old and new scrap	99.99% Cu
Apparent Consumption	The sum of Primary Production + Old and new scrap + Refined Imports - Refined Exports ± Refined Stock Change	99.99% Cu
Net Import Reliance	The ratio of Imports to Apparent Consumption	%
Concentrated Copper	Material produced from concentrated ore prior to smelting	30% Cu
Matte Copper	Material out of smelting of sulfide ores	40-70% Cu
Blister Copper	Matte copper processed in a furnance	98-99% Cu
Anode Copper	Unrefined copper from smelting prior to electrolytic refining	98-99.5% Cu
Cathode Grade Copper	Refined copper from electrowinning or electrolytic refining	99.99% Cu
Unrefined Import	Blister (made from matte copper) and copper anode (from smelting)	98-99%
Unrefined Export	Blister (made from matte copper) and copper anode (from smelting)	98-99%
Old Scrap	Post-consumer scrap, not waste from manufacturing	
Mine Capacity (USGS)	Copper content based on ore concentration and material handling capacities at mine sites	Cu

Historical Production

An invaluable resource for understanding Cu supply and demand in the U.S. is the USGS, which has reported annually on important statistics of the Cu industry in the U.S. for over 8 decades in the form of Minerals Yearbooks (presently up to year 2021) and Mineral Commodity Summaries (presently up to year 2025). Notable nation-level data includes statistics on total ore sent to concentration processes (capacity), economically Recoverable Cu from processing (Fig 1c), and Primary Cu. Primary Cu is refined Cu produced by either electrolytic or electrowon processes.

An estimated 80% of global primary Cu comes from the pyrometallurgical pathway that relies on various furnaces for smelting of sulfide ores. Primary sulfide ore, i.e. chalcopyrite $CuFeS_2$ has a hardness of 3.5-5 on the Mohs scale, while secondary sulfide ores such as chalcocite Cu_2S have a hardness of 2.5-3. Copper is an element in numerous other minerals that have been mined for centuries, including the oxide ore malachite ($CuCO_3Cu(OH)_2$; hardness of 3.5 - 4). Porphyry copper deposits, which tend to be mined using surficial open-pit methods, frequently produce molybdenum, silver, and gold as primary or secondary products. Notable examples in the state of Arizona, U.S. include the Bagdad Mine, active as early as 1917, and the Morenci Mine, active as early as 1872. Sulfide copper ores from these mines are harvested from blasted and hauled materials that are ground down for Cu separation. While some underground mines for Cu exist in the U.S., such as the Eagle Mine in Michigan, the majority of active Cu production occurs at open-pit mines. Methods such as dump leaching, or froth flotation and thickening are used to concentrate prior to smelting. Copper sulphide concentrate (~30% Cu) is then further processed at smelters into matte, then anode-grade and finally cathode-grade (99.99%) Cu product and by-product sulfuric acid.[12] A by-product referred to as anode slime is rich in gold, silver, selenium, and tellurium and sold to metal recovery facilities. As of 2024, The USGS reports two primary smelters in operation (Miami in Arizona and Kennecott in Utah), while there are speculations of Ascaro by Grupo Mexico reopening Hayden in Arizona. Based on feed rates, we estimate Kennecott has a capacity of 2.1 MMT/year concentrate/feed while Miami can process 0.8 MMT/year concentrate/feed. Hayden could contribute an additional 0.67 MMT/year, making for a total of more than 3.5 MMT/year concentrate/feed processing capacity. Investments to bolster domestic sources of Cu are likely to require increased processing capacities for both SX-EW and smelting and refining of primary and scrap copper.[14]

Twenty percent of global primary Cu is derived from hydrometallurgical pathways that entail ore leaching followed by SX-EW. While Cu production has historically and globally been dominated by pyrometallurgical recovery, hydrometallurgical recovery has contributed more than 40% of primary production in the U.S. since 2010, rising steadily to 61% in 2021 due in part to the decline of electrolytic Cu (Fig 1d). Mines that primarily generate oxide copper ores, such as the Lisbon Valley Mine in Utah also gather Cu from open-pit methods. However, instead of flotation and thickening, reagents like sulfuric acid or hydrochloric acid are used to dissolve Cu minerals into a collection area where the "pregnant" leachate is sent to SX-EW to reach high purities (99.99% Cu). Heap leaching techniques allow companies to process oxide ores, return to tailings waste piles, while *in-situ* recovery involves injection of solutions into the ore deposit. *In-situ* leaching, which involve subsurface extraction of Cu through well injection and recovery in porous deposits, has been proposed at the Gunnison mine, Van Dyke Project, and Florence Project in Arizona.

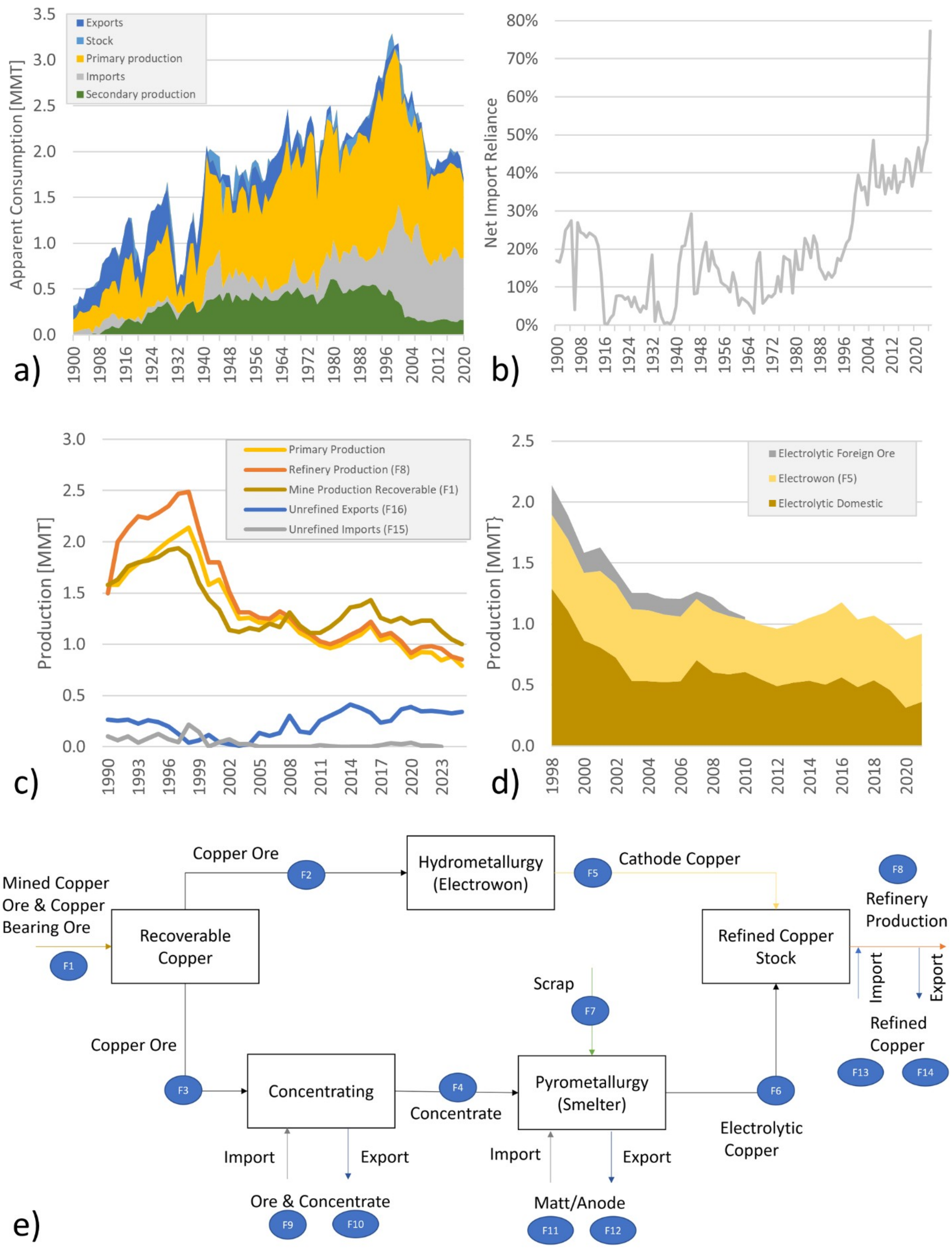

Figure 1. Historical a) apparent consumption of Cu in the United States; b) ratio of imports to apparent consumption; c) domestic and international primary Cu sources; d) refining of domestic and international ore. E) Flows describing primary Cu production from domestic and international sources are provided.

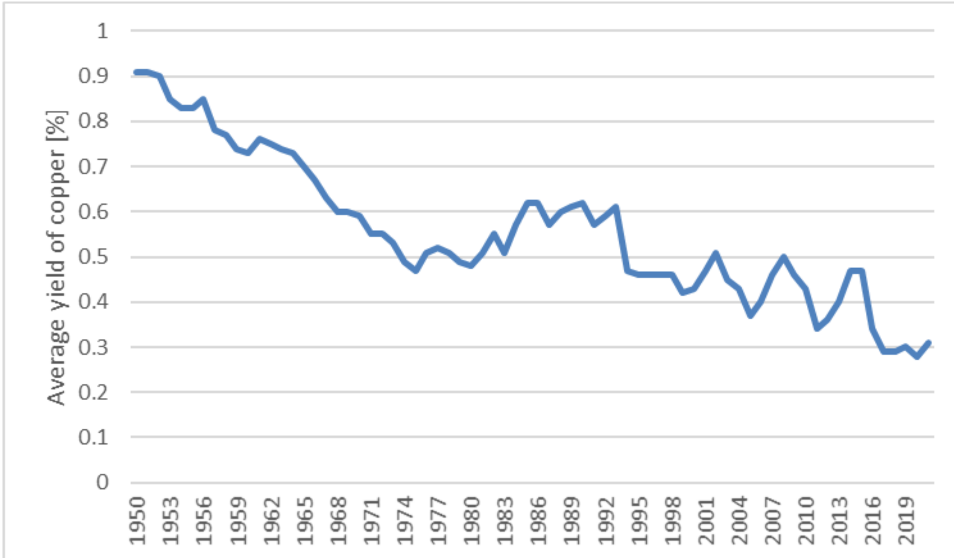

Figure 2. Average yield of copper from domestic copper ores concentrated, reported by mines. USGS Minerals Yearbook 1955 through 2021.[2] Value can be considered the average ore grade of raw ore ultimately concentrated through milling and floatation. This value does not include copper recovered by solvent extraction and electrowinning.

The Cu production capacity of top producing mines are reported annually by the USGS, with capacity reflecting the recoverable Cu content of material processed through SX-EW (F5) or concentration and smelting (F6) (Table E1) based on ore grade and equipment sizes. Capacity, split by production pathway (electrolytic or electrowon), is approximated based on primary mine activities, with poor agreement between electrolytic capacity and actual Cu concentrate statistics (Table E1). While the USGS notes whether leaching practices are used, the exact breakdown of Cu derived from each mine for electrolytic or electrowon primary Cu production is not specified. Mines that once specialized in concentrate for smelting (F4) are now advancing projects for alternative Cu production, with 13 open-pit mines now leaching in some capacity in the U.S. (Table E2). Between the years 2012-2021, reported primary Cu (F8) was between 49-69% of mine capacity, highlighting how actual annual production is lower than capacity. Despite capacity numbers holding relative constant over that period for all mines remaining in operation, production of concentrated ore varies year to year due to a range of factors including ore grades, maintenance, weather, and other run-of-mine decisions. Variations on process efficiencies can also lead to variations in Cu yield and Recoverable Cu. Mines run on tight profit margins, and Run-of-Mine decisions are sensitive to geopolitical trends beyond the scope of this study. As of 2021, there were 2 smelters and 14 electrowon refineries for primary Cu production.

Methodology

Mine characteristics

A list of Cu mines is developed for this study by reviewing USGS reports,[152] Holley *et al*,[11] lists of prominent open-pit mines,[16] internet queries, mine company webpages, and public industry intelligence databases.[17] All projects were verified for address and any visually apparent mine surface area using Google Earth. Nearly all domestic primary Cu production is produced at less than 20 mines. We include 18 mines as active mines based on historical data from the USGS (Table E1), and identify 26 additional mines or mine projects in various stages of development, from proposed greenfield, to restart, to advanced development (Table E2). Mines must provide a NI 43-101 or prefeasibility reports to be included. We note that the Gunnison Project in Arizona reflects several satellite projects started in 2025 intended to extend operations of the SX-EW, including Johnson Camp, Strong & Harris, and South Star, the latter of which was excluded due to limited data. Characteristics collected include: mine name, county, state, latitude, longitude, address, owner, primary commodity, type of mine, activity status, start year, type of ore, ore grade, strip ratio (waste: ore), concentrator processing rate, smelter rates, recoverable copper, payable metal, concentrate, and cathode copper. Copper ore grades vary by mine and year reported, and ranges were gathered to represent most probable current ore grade levels. Disclosure reports were used preferentially to provide information on mineral resource statements and smelter terms.

Ore sent to processing (F2 and F3) is already less than the raw rock extracted at mines. Total throughput of rock or ore excavated is rarely reported, whereas the capacity for processing concentrated ores are commonly reported by mines producing Cu concentrate for smelting. A theoretical minimum ore production rate can be approximated by dividing annual cathode grade Cu production (99.99% Cu) by the original ore grade. For example, an ore grade of 0.5% would yield 200 tonnes of ore for every 1 tonne of cathode grade Cu. When compared with reported ore processing rates, we find this method is a poor predictor, and generates estimates ranging from 1 to over 500% of reported ore processed. Mine schedules for mine projects such as the CK Gold Project indicate the fraction of material mined that is ore can swing between 33 to 67% over just a few years. Adjusting for Cu grade, the Cu content of rock ranges from 0.06% to 0.14%. In comparison, reported representative ore grades are presented as life-of-mine static averages. Goonan estimates 316 tonnes of rock bearing 0.5% Cu for every 1 tonne of cathode grade Cu produced (0.32% yield from rock) (Fig 4 of Goonan USGS)[6]. For hydrometallurgy, the estimate is 510-5100 tonnes of ore at 0.1-1% Cu leached for every 1 tonne of cathode grade Cu (0.019 to 0.19% yield from rock) (Fig 5 of Goonan USGS)[6]. Holley *et al* suggest using geochemical characteristics of ore deposits to improve estimates of ore grades and critical mineral concentrations beyond target minerals.[11]

Instead of these theoretical approaches, to estimate ore processed and material excavated, we use strip ratios and concentrator ore processing capacities (Table 3). For example, the Arctic Project reports a high strip ratio of 7.3:1, with a 92.1% average recovery of Cu, while the Pumpkin Hollow reports a low underground/open-pit strip ratio of 3.1:1 One of the lowest strip ratios was identified at the Continental mine at 1.2:1 when considering material excavated to ore hauled to primary crushers. The Cactus mine (leaching) suggests a strip ratio of 3.3:1 and 75% global recovery, while the Gunnison mine (leaching) suggests a strip ratio of 2.26:1 and 68% global recovery. The Florence leaching project projects a 65.8% recovery. Clearly no single generalized factor can accurately represent mass excavated, ore produced, or gangue generated.

For active mines, production in terms of cathode grade Cu are compared with totals for Electrolytic and Electrowon Primary Cu last reported by the USGS (2021). For open-pit or underground mines producing ore for smelting, the product sent offsite is copper concentrate. Concentrator equipment capacity (ore processed) and concentrate production are frequently reported as mines transport this product between the milling and smelting facilities and must agree to smelting terms (F4). Some mine projects provide both Metal in Concentrate and Concentrate, allowing us to derive Cu contents of 23% for Black Butte, 25% for Copperwood and Copper Flat, 26% for Pebble Project and 30% for Mason. The CK Gold project reports a minimum concentrate Cu content at 17%. IN most cases, concentrate falls closer to 30% and we assume Cu content to be 30% when a value was not identified. Equations for conversions between Cu products are included in the ESI. Payable metal reflects a negotiated percentage of Cu in concentrate sent to smelters and is not equivalent to F4. We use a value of 96.5% when converting Payable Metal to Concentrate (value reported in Smelter Terms for many projects such as Copper Flat and Copperwood), which also suggests a 3.5% loss rate between concentrate and cathode grade Cu. Smelters convert copper ore, ash ore, concentrate, and matte from imports and domestic sources. Matte is the product that comes out of smelting furnaces prior to refining and contains between 50 and 70% Cu. Anode Cu (99%) or blister grade Cu (98% Cu) is then sent to electrolytic production to produce cathode grade Cu. Refined Cu may be reported as cathode grade copper (F5 and F6). There are presently two large pyrometallurgic smelting facilities for primary Cu active in the U.S.: the Miami Freeport-McMoRan smelter in Arizona and the Rio Tinto Kennecott smelter in Utah. which sets a bottleneck rate of domestic production from conventional sulphide ores. A major consideration for mines such as the Pebble Project, which is a proposed greenfield mine located in Alaska, is where copper concentrate would be smelted, and how electricity and fuels would be provided to this remote site. While we include new production as potential domestic supply, technical reports suggest unrefined concentrate will be exported for processing. Notably, the Copper Flat and CuMo Projects describe smelter terms assuming shipment of concentrate to smelters in Asia, according to their NI 43-101 reports.

LCA Representation

When considering life-cycle representations of Cu supply, Cu is included under mining of non-ferrous metal ores. Energy and environmental impacts associated with Cu production have been studies for decades, with early estimates of theoretical energy demand (0.48 kWh/kg-Cu) reported in 1974.[18] We use Cu as a search term for processes in the ecoinvent 3.10 database[19] (adapted for OpenLCA 2.0.4), removing pathways for copper sulfate (pentahydrate) and copper carbonate which are industrial chemicals. Copper concentrate (F4) is converted into anode and cathode-grade copper (F6) products through smelting and refining processes. Copper concentrate is derived from a number of mining activities, including cobalt, gold, gold and silver, nickel, zinc, molybdenite, and platinum ground metals primary production (F3). To a limited degree, hydrometallurgical pathways are included that represent SX-EW (F5), however the diversity of processes under this classification are poorly captured. For example, roasting requires high energy consumption but is not represented. Secondary sources of Cu are included in LCA databases, including the recycling of scrap (F7) and batteries. *In-situ* Cu recover is not yet represented in ecoinvent 3.4.

Processes were organized based on functional unit to develop complete emission factors from primary earth resource to final product of copper cathode. This was necessary as intermediate units include concentrate, cake (from cobalt and zinc), anode, and anode slime stockpile. Pathways with product forms including wire and sheet were excluded (fabrication processes following F8). Global pathways were selected, except for copper mining and beneficiation of sulphide copper ore which offered a U.S. value. Flow providers were selected using U-cut off, which assigns impacts to the source of waste and which does not assign impacts to materials that are recycled. Factors for diesel, water, electricity, and waste tailings were gathered and compared with values reported in literature. Another reference point for mine activity is diesel fuel usage. Diesel consumption at 10 individual open-pit Cu mines were compiled by Szum and Breunig (2025) from company Scope 1 greenhouse gas emissions reporting documents.[16] The report presents a rigorous assessment of diesel consumption, including a data quality and source reliability matrix. We normalize mine-specific fuel usage with our estimates for total mass excavation and ore processing at those mines, and compare resulting fuel usage factors with those reported in literature. For open-pit mines without estimates, we assume the lower value factor in Memary et al. We note that equipment and some operational cost estimates are reported in technical reports for mine projects but truck schedules and fuel consumption are not clarified.

Results

Based on gathered start years, the active mines in the U.S. have operated for a combined 1,427 years, with some of the oldest mines operating for over 150 years. Copper mining activity is concentrated in the Southwest region, where 11 new projects are also proposed, mostly in Arizona (Fig 3). Many new projects under various stages of evaluation and development have emerged in Idaho, the Great Lakes region, and Alaska. Established companies such as Rio Tinto have proposed projects, however many proposed projects are backed by emerging Cu producers. We identify three greenfield sites, while most other projects are located in regions famous for mining, with established mining-oriented communities and industry. Notably all active mines are open-pit except the underground nickel-copper Eagle mine. Thirteen active mines operate leaching projects, with Tyson, Phoenix, Carlota primarily leaching and Lisbon Valley and Miami focusing on in-situ processes. We estimate most of the copper from Chino is now derived from leaching. In comparison, twelve proposed mines are underground with two in-situ. Three projects primarily use leaching (Santa Cruz, Gunnison, Cactus), although several have plans for mixed reliance on open-pit concentrate and leaching. This suggests future Cu activities may have a smaller land footprint. Only two proposed primary Cu projects identify as mines as they are "restarting" mines, whereas all other are "projects" either focused on a new deposit at an existing mine, or identified short-term source of Cu for recovery.

Mine activity

We find a cut-off ore grade value of 0.45%[20] captures the non-weighted average of the lower bound grade of the 44 mines (0.52%) (Table 2), but does not capture the heterogeneity of ore qualities in active and proposed Cu projects. We find average lower bound ore grades of 0.29% for in-situ mines, 0.45% for leaching dominated mines (mainly relying on oxide ores), and 0.55% for concentrate dominated mines (mainly relying on sulfide ores). In contrast, the upper bounds are 0.53%, 1.11, and 1.26%, respectively. In comparison, in 1980 average concentrate was at <0.6%.[1] Several older active mines, including Ray, Bingham, Eagle, Mission, and Miami report possible ores with >1.5% Cu, while mines like Black Butte and Arctic offer the possibilities of ores with >2.5% Cu. These values do not include highest reported ore grades that have been discovered, but rather economically recoverable ores over proposed life-of-mine periods.

USGS estimate primary Cu production capacity at 17 active mines is 1.9 MMT/year in 2024, with a five year average of 0.871 MMT/year (0.790 to 0.922) of primary production. We identified 0.925 MMT/year cathode grade Cu production at active mines (Table 2), showing remarkable agreement (6% difference). We were able to find primary source data for either concentrate, payable metal, or cathode grade Cu production from technical company reports for 100% of mine projects, with 34 out of 44 mines projects offering values for the cathode grade Cu (100% for active projects and 62% for proposed projects). The mines requiring conversions across Cu products to obtain cathode grade Cu represent 31% of annual production. The USGS estimates as high as 64% of recent domestic primary production stems from electrowon processes. We distinguish only 16% of reported cathode grade Cu stemming from active leaching dominated mines, suggesting as noted by USGS, that many active mines have leaching projects contributing further to electrowon production. When using the absence of reported Cu concentrate production as an indicator of leaching (suggesting leaching products are sold rather than concentrate), the contribution of leaching rises to 67% of annual cathode production. Total reported copper concentrate production at active mines is 1.1 MMT /year. Cu cathode production reported in Holley *et al.* for 15 active mines are within ±26% of our estimates for 9 mines, with Silver Bell and Safford reporting much lower production (Table E1).

While uncertain, it is remarkable that new projects feature 2.2 MMT/year of additional copper concentrate (Fig 4). We identify a promising total of 1.6 MMT/year of reported cathode-grade copper production from new projects. Of this, roughly 21% is leachate that would go through a SX-EW process, whereas the rest appear to be sulphide ore concentrate sources that would need smelting capacity. Most of these projects are expected to be short-lived, spanning 5-20 years, while greenfield mines are expected to operate at high ore-grade levels for 20+ years. In total, this could lead to 3.3 MMT/year concentrate to smelters, necessitating processing offshores, the opening of a smelter such as Hayden, AZ, or the construction of a new smelter.

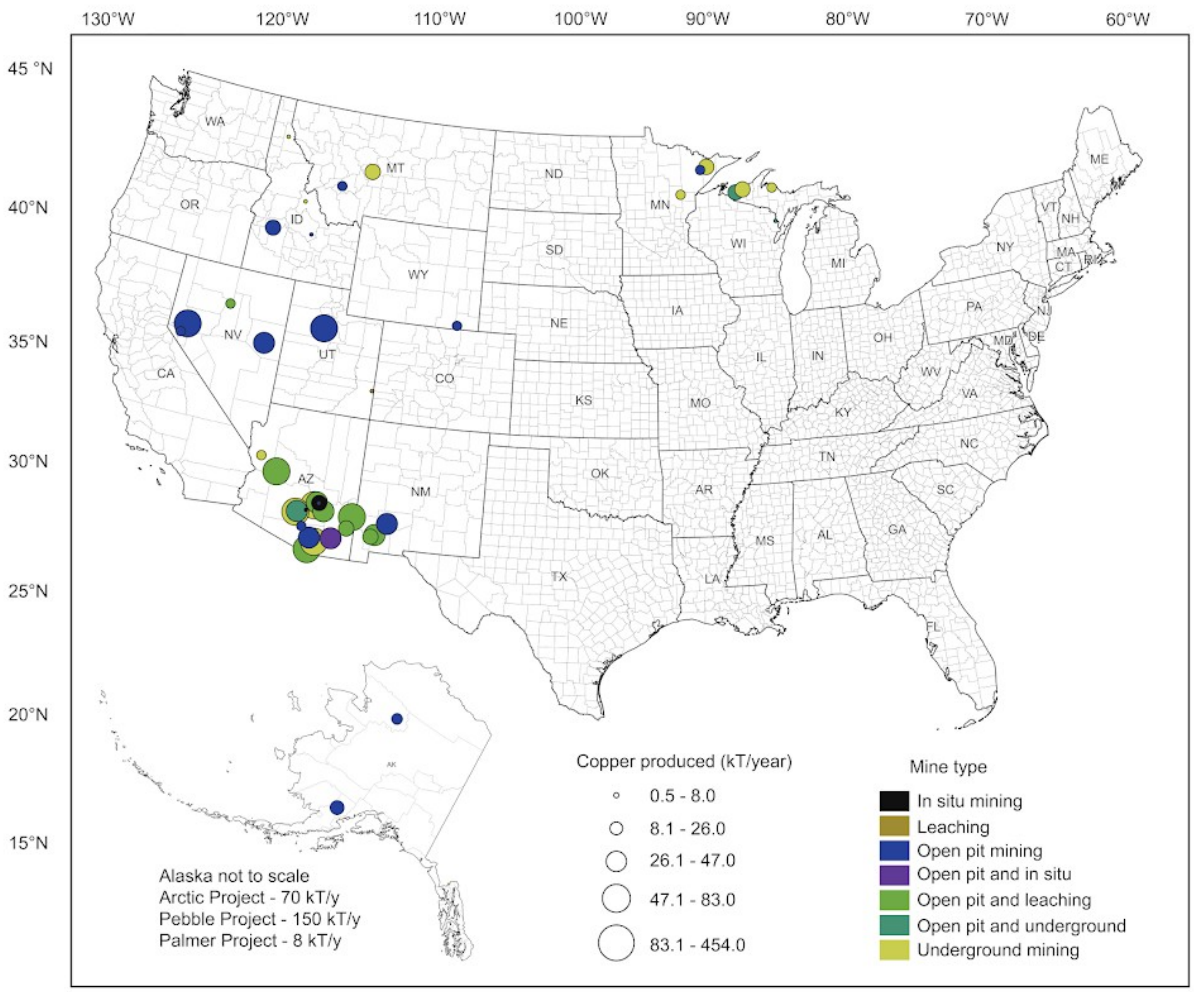

Figure 3. Map of active and proposed primary copper mines in the contiguous United States and Alaska. Size of circle indicated estimated annual production rate of cathode grade copper.

Figure 4. Contribution of new proposed mine projects to domestic primary cathode grade copper production in the United States.

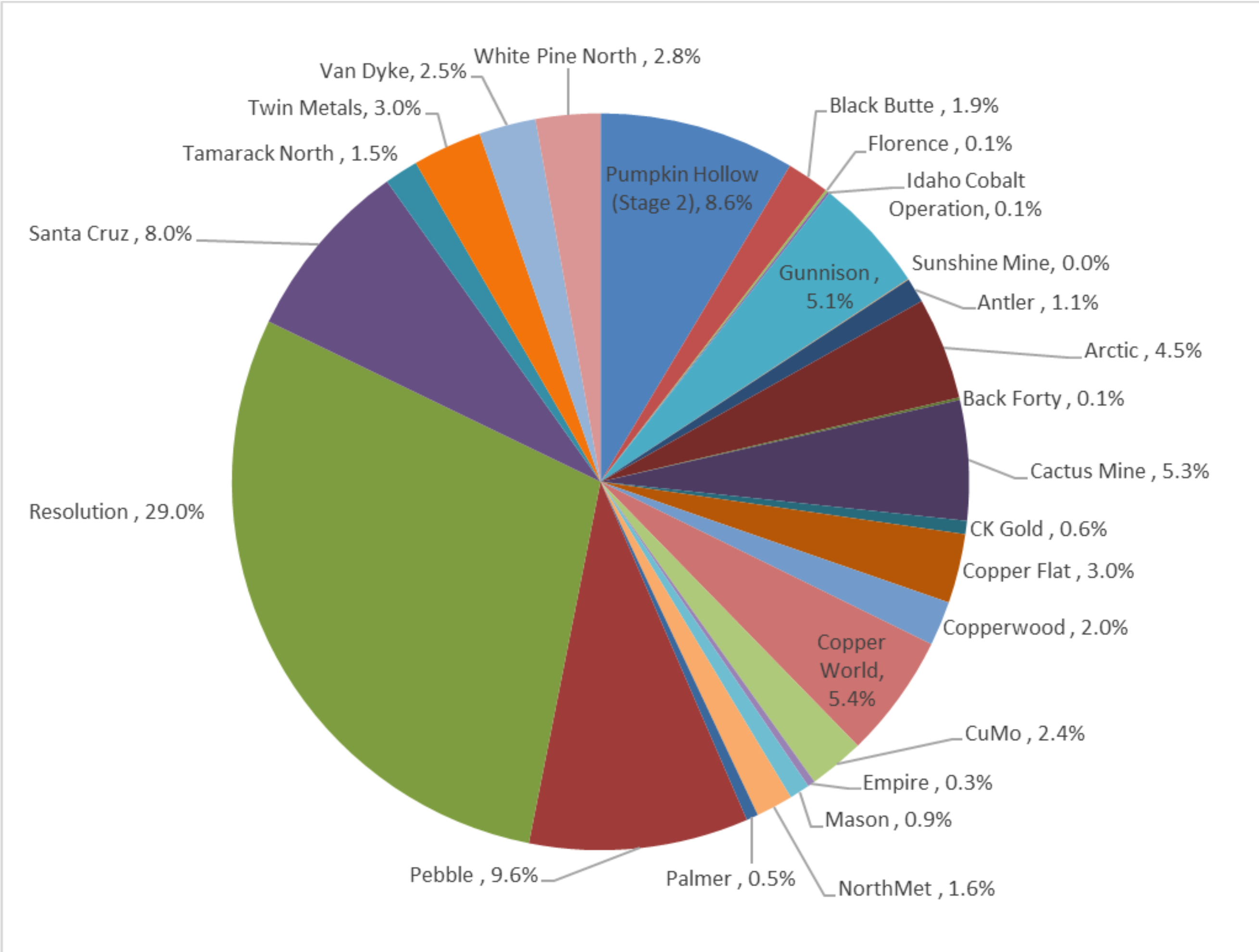

Table 2. Mining activity at active and proposed copper projects from most recent reports (2021 to 2025). Units in thousand metric tonne per year. "Leaching" or "In Situ" indicated when the mine does not produce concentrate for smelters. Values in *italics* are calculations using assumed conversion factors.

#	Mine Name	State	Copper Grade (low)	Copper Grade (high)	USGS 2018 Capacity	Processing Rate (F3 & F2)	Recoverable	Copper Concentrate (F4)	Cathode Grade Copper (F5 & ~F6)	Payable Metal (F6)
							Thousand tonnes/year			
1	Bagdad Mine	AZ	0.29%	1.10%	110	28,142		*355*	107	
2	El Chino/Cobre Mine	NM	0.30%	0.45%	145	*26,748*		*38*	68	
3	Kennecott Copper Mine (aka Bingham Canyon)	UT	0.47%	1.90%	220	60,351			193	
4	Mission Complex Mine	AZ	0.50%	2.00%	75	19,601		*193*	55	
5	Morenci Mine	AZ	0.16%	0.30%	580	18,250			102	
6	Pinto Valley Mine	AZ	0.25%	0.36%	65	14,600		194	61	
7	Ray Mine	AZ	0.40%	1.73%	133	10,950		131	56	
8	Safford/Lone Star Mine	AZ	0.25%	0.40%	110	45,867			27	
9	Sierrita Mine	AZ	0.24%	0.39%	110	45,062			86	
10	Tyrone Mine	NM	0.10%	0.79%	45			Leaching	45	
11	Robinson Mine	NV	0.25%	0.80%	65	16,060			56	
12	Continental Pit Mine	MT	0.20%	0.40%	40	20,117		172	19	
13	Silver Bell Mine	AZ	0.20%	0.69%	21	1,609		Leaching	21	
14	Eagle Mine	MI	1.00%	2.00%	25	730		35	10	
15	Phoenix Mine	NV	0.16%	0.40%	30	12,775			9	
16	Lisbon Valley Mine	UT	0.51%	5%		7,242		Leaching	3	
17	Miami Mine	AZ	0.26%	1.50%	90			Leaching	7	
18	Carlota Mine	AZ	0.20%	0.45%	35			Leaching	3	
19	Pumpkin Hollow Project (Stage 1)	NV	0.25%	0.69%	NA				1	
19	Pumpkin Hollow Project (Stage 2)	NV	0.25%	0.69%	NA	24,834		316	134	
20	Black Butte Project	MT	1.90%	2.90%	NA	1,200		129	*29*	28
21	Florence Project	AZ	0.32%	0.40%	NA			In situ	2	
22	Idaho Cobalt Operation	ID	0.68%	0.80%	NA	265		*10*	1	
23	Gunnison Project (Excelsior Mine)	AZ	0.29%	0.85%	NA	29,030	81	In Situ & Leaching	69 to 79	
23	Johnson Camp (Gunnison satellite)	AZ	0.29%	1.00%	NA			Leaching	11	
23	Strong & Harris (Gunnison satellite)	AZ	0.56%	0.85%	NA			Leaching	28	
24	Sunshine Mine	ID	0.21%	0.83%	NA	315		2	1	
25	Antler Project	AZ	2.10%	2.10%	NA	1,200	22	*62*	*17*	16
26	Arctic Project	AK	2.11%	5.00%	NA	3,650		234	*70*	68
27	Back Forty Project	MI	0.10%	0.41%	NA	1,752	3	*10*	*2*	2
28	Cactus Mine Project	AZ	0.48%	0.52%	NA	28,000	90 to 103	Leaching	82	78
29	CK Gold Project	WY	0.13%	0.23%	NA	6,600		55	*9*	
30	Copper Flat Project	NM	0.25%	0.35%	NA	11,909	47	187	*47*	46
31	Copperwood Project	MI	1.43%	2.00%	NA	2,482		55	*31*	29
32	Copper World Complex	AZ	0.37%	0.54%	NA	21,900			47 to 85	
33	CuMo Project	ID	0.12%	0.20%	NA	54,750		*127*	38	
34	Empire Project	ID	0.10%	0.49%	NA	1,606			5	5
35	Mason Project	NV	0.20%	0.29%	NA	43,800		112	14	
36	NorthMet Project	MN	0.20%	0.60%	NA	12,487		27	*25*	24
37	Palmer Project	AK	0.57%	1.69%	NA	1,278		*29*	*8*	8
38	Pebble Project	AK	0.30%	0.40%	NA	65,700	156	559	*150*	145
39	Resolution Project	AZ	1.50%	1.50%	NA	48,180			454	
40	Santa Cruz project	AZ	1.80%	1.80%	NA			Leaching	125	
41	Tamarack North Project	MN	0.25%	2.34%	NA	507		24	*23*	
42	Twin Metals Minnesota Project	MN	0.59%	0.69%	NA	7,300		158	*47*	
43	Van Dyke Project (within Miami)	AZ	0.27%	0.33%	NA	2,268		In Situ	29 to 39	
44	White Pine North Project	MN	0.90%	1.07%	NA	5,475		*147*	*44*	43

Table 3. Estimation of annual ore and excavated material production by mine. Values in *italics* are calculations using assumed conversion factors. Water and Global Warming Potential (GWP) include refining processes, while other values are for mine-site only. LOM: Life-of-Mine.

#	Mine Name	State	Primary Activity Type	Strip Ratio	Material Excavated	Ore Processed	Gangue	Diesel	Electricity	Water	GWP	Sulfide Tailings
					LOM average thousand tonnes/yr			Million GJ/yr	GWh/yr	Thousand m3/year	Thousand Tonnes CO2e/yr	Thousand tonnes/yr
1	Bagdad Mine	AZ	Open-pit	2	75,982	28,142	47,841	2	469	7,462	1,813	7,226
2	El Chino/Cobre Mine	NM	Open-pit	3	106,991	26,748	80,243	1	299	11,560	1,157	36,575
3	Kennecott Copper Mine (aka Bingham Canyon)	UT	Open-pit	3 to 5	301,757	60,351	241,406	8	849	13,510	3,283	13,083
4	Mission Complex Mine	AZ	Open-pit	3 to 5	98,003	19,601	78,402	0	242	3,850	936	3,728
5	Morenci Mine	AZ	Open-pit	2 to 4	73,000	18,250	54,750	7	449	7,144	1,736	6,919
6	Pinto Valley Mine	AZ	Open-pit	1	35,040	14,600	20,440	1	266	4,235	1,029	4,101
7	Ray Mine	AZ	Open-pit	3	43,800	10,950	32,850	2	246	3,919	952	3,795
8	Safford/Lone Star Mine	AZ	Open-pit	3	183,468	45,867	137,601	3	119	1,890	459	1,830
9	Sierrita Mine (focusing on stockpile)	AZ	Open-pit	0	49,569	45,062	4,506	2	377	5,999	1,458	5,810
10	Tyrone Mine	NM	Leaching	0	14,157	10,112	4,045	1	198	7,650	765	24,204
11	Robinson Mine	NV	Open-pit	3 to 4	72,270	16,060	56,210	1	246	3,914	951	3,790
12	Continental Pit Mine	MT	Open-pit	1	44,258	20,117	24,141	2	84	1,330	323	1,288
13	Silver Bell Mine	AZ	Leaching	2	4,667	1,609	3,058	0	92	3,570	357	11,295
14	Eagle Mine	MI	Underground	-	730	730	-	-	211	700	170	678
15	Phoenix Mine	NV	Leaching	-	12,775	12,775	-	-	38	1,462	146	4,625
16	Lisbon Valley Mine	UT	Moving to In-situ	3.61 (older)	33,386	7,242	26,144	1	57	463	46	-
17	Miami Mine	AZ	In-situ	-	-	-	-	-	143	1,156	116	-
18	Carlota Mine	AZ	Leaching	-	800	800	-	-	11	442	44	1,398
19	Pumpkin Hollow Project (Stage 1)	NV	Open-pit	3	-	-	-	-	5	84	21	82
19	Pumpkin Hollow Project (Stage 2)	NV	Open-pit	3	109,271	24,834	84,436	2	591	9,398	2,284	9,102
20	Black Butte Project	MT	Underground	-	1,200	1,200	-	-	617	2,048	498	1,984
21	Florence Project	AZ	In Situ	-	-	-	-	-	37	298	30	-
22	Idaho Cobalt Operation	ID	Underground	-	265	265	-	-	32	105	25	101
23	Gunnison Project (Excelsior Mine)	AZ	Leaching	2	94,638	29,030	65,608	2	348	5,530	1,344	42,492
23	Johnson Camp (Gunnison satellite)	AZ	Leaching	2	-	-	-	-	348	1,928	193	6,099
23	Strong & Harris (Gunnison satellite)	AZ	Leaching	3	-	-	-	-	348	4,781	478	15,126
24	Sunshine Mine	ID	Underground	-	315	315	-	-	11	36	9	34
25	Antler Project	AZ	Underground	-	1,200	1,200	-	-	357	1,185	288	1,147
26	Arctic Project	AK	Open-pit	7	30,295	3,650	26,645	0	308	4,903	1,191	4,748
27	Back Forty Project	MI	Open-pit	4	9,286	1,752	7,534	0	8	121	29	117
28	Cactus Mine Project	AZ	Leaching	2	89,600	28,000	61,600	2	362	13,977	1,399	44,223
29	CK Gold Project	WY	Open-pit	1	12,540	6,600	5,940	1	40	636	155	616
30	Copper Flat Project	NM	Open-pit	0	16,673	11,909	4,764	1	209	3,321	807	3,216
31	Copperwood Project	MI	Underground	-	2,482	2,482	-	-	645	2,139	520	2,071
32	Copper World Complex	AZ	Open-pit	2	54,750	21,900	32,850	2	374	5,950	1,446	5,762
33	CuMo Project	ID	Open-pit	3	219,000	54,750	164,250	5	374	2,667	648	2,583
34	Empire Project	ID	Open-pit	2	4,320	1,606	2,714	0	374	354	86	343
35	Mason Project	NV	Open-pit	2	131,400	43,800	87,600	4	374	980	238	949
36	NorthMet Project	MN	Open-pit	2	34,964	12,487	22,477	1	374	1,777	432	1,721
37	Palmer Project	AK	Underground	-	1,278	1,278	-	-	170	562	137	545
38	Pebble Project	AK	Open-pit	0.12 (1.67 older report)	73,584	65,700	7,884	6	661	10,518	2,556	10,186
39	Resolution Project	AZ	Underground	-	48,180	48,180	-	-	9,579	31,780	7,723	30,777
40	Santa Cruz project	AZ	Underground, Leaching	0	7,778	6,944	833	-	2,638	21,250	2,126	67,234
41	Tamarack North Project	MN	Underground	-	507	507	-	-	489	1,621	394	1,570
42	Twin Metals Minnesota Project	MN	Underground	-	7,300	7,300	-	-	1,000	3,318	806	3,213
43	Van Dyke Project (within Miami)	AZ	In Situ	-	2,268	2,268	-	-	823	6,630	663	-
44	White Pine North Project	MN	Underground	-	5,475	5,475	-	-	932	3,093	752	2,995
Total				-	2,103,745	716,974	1,386,771	57	26,823	221,244	43,018	389,383
Open-pit				-	1,673,229	527,989	1,145,240	49	7,039	93,962	22,833	90,995
Leaching				-	394,862	179,475	215,387	7	18,723	118,736	19,330	298,388
In-situ				-	35,654	9,510	26,144	1	1,061	8,547	855	-

Projected Energy, Waste, and Water Flows

Energy, water and waste production characterization factors were compiled and are discussed in the ESI Section Life Cycle Assessment, including factors for non-Cu mines where Cu is a by-product. Annual consumption for diesel, electricity, and water, and the production of gangue, tailings waste, and greenhouse gas emissions are presented in Table 3. When considering all 44 mine projects, we find that 87% of diesel consumption is associated with open-pit activities. Mine projects that generate concentrate consume 26% and 42% of electricity and water, respectively, and account for 53% of GWP for primary refined Cu production. New Cu mine projects would double annual diesel consumption, and more than double annual water consumption and greenhouse gas emissions from domestic primary Cu production. Due to the large number of underground operations proposed, electricity consumption could increase by 6x.

Mining activities require blasting, as well as diesel hauling trucks, bulldozers, graders, excavators, loading belts, trolleys, generators and local locomotives. Diesel mobile equipment dominates energy consumption for mining (24-66%), while grinding and concentration require the majority of energy in beneficiation (32-45%).[12,21] Overall, diesel consistently represents more than 50% of energy for open-pit mine operations pre-processing. For open-pit mines, purchased or onsite generation of electricity and heat are generally used to power buildings and equipment such as electric shovel loaders, drilling, and pumping for dewatering and sprinklers. Agitation and comminution of ore or heap piles via processes such as grinding (diesel) or ball milling facilitate higher reactive surface areas while flotation and magnetic separation are intended to increase concentrations prior to pyrometallurgical or hydrometallurgical refining. In general, the ores that contain Cu are soft, and physical comminution has received less focus in comparison to aggregate and basalt mines that manage harder rocks. In contrast, for oxide copper ores where no smelting occurs, SX-EW processes leverage grid or dedicated electricity generation, at more than 80% of cumulative energy demand.[22] Half of this demand is associated with electrowinning which requires high voltages.[23] The electrowinning process involves the conversion of copper ions to solid copper, with a reduction potential of +0.34 V and theoretical minimum of 0.75 kWh/kg-Cu. In practice electrical consumption will be higher to overcome overpotentials and inefficiencies.

In general, lower grade ores require more transport and processing of rock and ore, increasing the environmental burden of the primary resource. As highlighted in Fig 5, we find that mine-level diesel consumption normalized for ore movement is on the same order of magnitude for all mines except Morceni which reports very high excavation rates. Still, the lower bound value by Memary and colleagues overestimate diesel consumption at mines that use a mix of leaching and traditional concentrate production, such as Chino. The same is true for diesel consumption normalized for mass excavated, however the lower range does not align with any active mine studied. This could be due to a range of factors, from non-truck consumption, to climate, to Run-of-Mine decisions not captured in fleet logistic models. While ore grade is a driver of fuel and electricity demand at mines, location will also play an important role in the suitability of fuel resource provision. For example, while the average state diesel price was \$3.57/gal as of February 2026, it has now risen to \$5.64/gal as of April 2026 due to geopolitical conflicts. This impact on remote areas has been seen before, with the aircraft delivered off-road diesel price for the Arctic mine Project in the Northwest Arctic Borough of Alaska at \$15.13/gal when adjusting on-road diesel prices for Federal and State taxes as of February 2026 due to geopolitical conflicts (Northwest Arctic Regional Energy Plan, 2022). In comparison, adjusted prices in the Southwest range from $2.40/gal to $3.11/gal prior to the Iran conflict, and now range from $4-5.2/gal. Inclement weather, winter closure of seaways due to ice,[24] and geopolitics can cause disruptions in fuel supply chains[25] to states without diesel refining capacity, particularly around the Great Lake and Alaska. Demand for diesel or diesel substitutes would need to align with the scale of consumption as well as location for supply chain and technical operation considerations. Very cold or hot weather would also present challenges to the deployment of Battery Electric Vehicles for mine operations.[21]

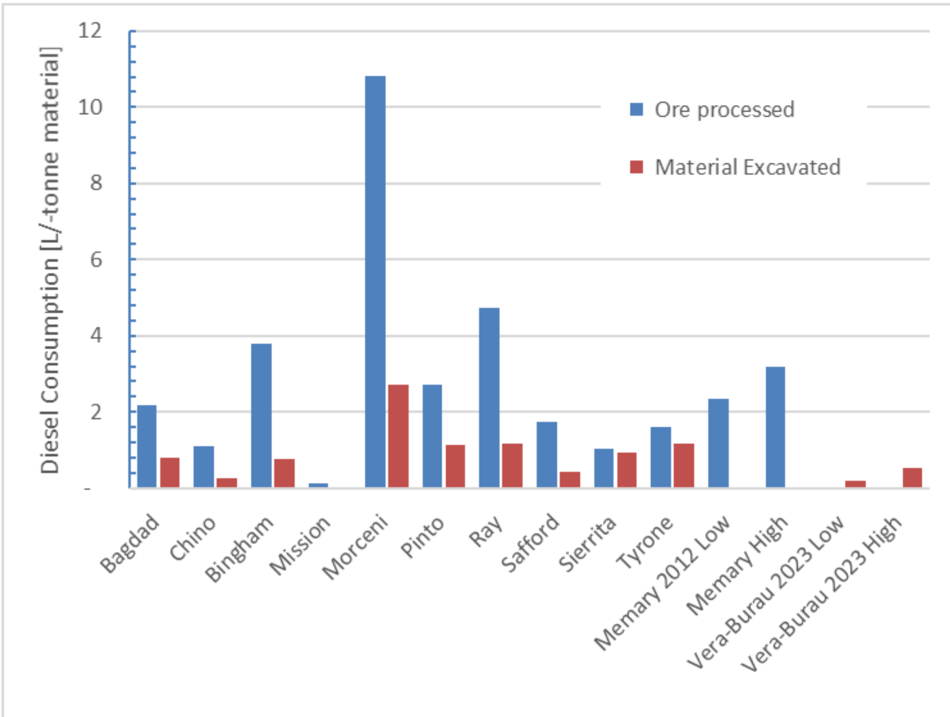

Figure 5. Diesel consumption (L/tonne-ore or L/tonne-excavated) by mine, compared with published fuel usage estimates.[26,27]

Copper mine operation and beneficiation in the U.S. is represented in ecoinvent assuming 130.8 kg gangue for every 1 kg of copper concentrate starting from a sulfide copper ore grade of 0.18%. Some of this material is used for backfilling, while other material is stored in tailings facilities. We estimate a much higher mean gangue production rates for open-pit mines primarily producing concentrate, of 407 (14 to 2000) kg-gangue/kg-concentrate. This is despite mines noting relatively "low" strip ratio of 3 or less. Including reported gangue from leaching and underground projects, we estimate 723 MMT of ore and 1,380 MMT per year of gangue is generated. Just considering open-pit mines primarily generating concentrate from sulfide ores, 1,672 MMT per year of waste post concentrate sales could be generated from 20 mines (active and proposed). Material flows in ecoinvent suggest oxide copper ore mines generate 8x more sulfidic tailings than a sulfide copper ore mines,[19] although these tailings are already leached at least once through the hydrometallurgical process. In total, as much as 389 MMT/year of tailings could be produced at domestic Cu mines. Such tailings are of interest to emerging practices for treatment to recover additional Cu or other critical minerals. Sulfide tailings have historically not been economical to process using leaching methods, as solvation of Cu and avoidance of off-target reactions of leaching solution requires meso or thermophilic activity and elevated temperatures. However, increasing Cu demand and novel technologies may shift mine production to include tailings. We note that alkaline tailings are of interest for enhanced weathering, with these materials coming from various mining activities including gold refining.

Data and Research Gaps

While extensive reviews of the metal sector have been conducted, accurate and updated models and related inventories of supply chains are lacking. This gap leads to tedious updates to mining activity and supply chain models, that are fraught with errors due to inconsistent public data related to operations and planned investments, limited reporting on operation conditions, and nascent methods for material tracing. Various sources are repetitive in their use of a primary source of data, often derived from a singular legal technical reports per mine. As such, there is presently not enough data in variable distributions for Monte Carlo Analysis to lead to meaningful representations of the sector. Scenario modelling for the implications of primary Cu production capacities at mines, smelters, and refiners is further complicated by inconsistent or imprecise terminologies for production units and misrepresentations of Cu production are common. While this gap remains an issue, this study contributes a consolidated dataset linked to geospatial coordinates for key metrics, including activity status, nature of mine, annual capacity and Cu production, and ore grades where explicit values are not provided. Mine productivity in terms of Cu concentrate and smelter or refinery productivity in terms of cathode grade copper are the basis of estimation of fuel and energy consumption, water requirements, wastewater management, and emissions. Activity levels are both evolving and uncertain, often locked behind paywalls or represented in outdated reports. We find a clear need for mine-specific and more detailed bottom up estimates at the process level.

Representation of emerging Cu activities including tailings treatment, heap leaching, and *in-situ* recovery is limited in LCA databases and literature. While *in situ* leaching originated in uranium mining and field trials or geochemistry and geophysical modelling efforts for Cu are nascent, recent process models have been presented that can be used in LCA, and leaching has become a major focus for research as data-driven approaches and new leaching agents develop.[28,29] As mines evolve, new types of energy demand may emerge at Cu mines. For example, the heating of heap piles during leaching can nearly double the cumulative energy demand of leaching methods.[22] Roasting of materials to prepare for smelting or leaching may also demand significant quantities of heat, especially for mines that extend operations into cooler seasons. Location-specific LCA pathways are lacking, although we acknowledge that mine-specific studies are limited in their generalizability but offer important data for bottom-up supply chain evaluation.[27] Country-level models for conventional ore concentrate production do not align with our estimates for material and energy flows when we evaluate operations at individual mines in the U.S.

Conclusions

Copper is an essential metal for numerous growing industries including the energy, transportation, and construction sectors. The IEA Global Critical Minerals Outlook 2025 forecast suggests that global supply of copper could peak this decade due to declining ores, projects with long lead times, and few new discoveries, resulting in a 30% deficit by 2035.[5] However, we find that in the U.S., ore grade quality at both existing mines and proposed projects trend higher than the low ore grades predicted for this decade, with promising annual Cu production growth. Existing active primary copper mine activities produce 1.1 MMT/year of reported concentrate and 0.9 MMT/year of cathode-grade copper, with capacity steady at

1.9 MMT/year. New projects could unlock 1.6 MMT/year of cathode-grade copper, resulting in a total domestic primary supply of 2.5 MMT/year cathode grade Cu. While 45% of new capacity is associated with projects starting before 2028, it is important to note that our results are for the average productivity over the Life-of-Mine and may reflect a 5 to 20 year supply with varying production yields across years. We estimate 976 MMT/year of waste is generated from active mines, with 1,672 MMT/year possible from all 44 mines evaluated. Based on ecoinvent factors, this may include as much as 389 million tonnes of sulfide tailings.

Boosting Cu production requires complex projects that present risks to companies, ranging from the uncertainty of ore grade, to exploration and permitting costs. Greenfield open-pit mines in sensitive areas such as Alaska are likely to continue to face opposition and long lead times for review. Long lead times can also arise for proposed surficial and underground projects in established mine areas if demand for resources such as water, electricity, and diesel exceed local provider infrastructure like substations. Despite the estimates presented in this study, exact requirements are uncertain, as consumption is sensitive to factors ranging from variable ore quality to shifts in technology adoption. New partnerships in copper supply are likely to arise as numerous proposed projects stem from emerging copper producers. We find frequent reference to offshore smelters in Technical Reports, and it is unclear the length of contracts developed that may hinder transitioning to any new domestic smelting capacity. As new smelters emerge, supply chain logistics will change, with unknown costs and potential market risks. For example, with the sharp increase in smelting capacity in China, heightened competition for copper feedstocks has led to swings in price. Heap leaching wastes and low-grade ores commonly occurs alongside open-pit and underground mining activities, generating a product that does not require smelting.

New projects will also place increased demand on water, electricity and diesel consumptions. Emerging technologies such as in-situ mining are proposed at three mines in Arizona. Historically, Cu has been recovered from open-pit mines, while many new proposed projects appear to use underground mining techniques. Project webpages make explicit note of reduced land footprint and surface disturbances. Underground mining consumes more electricity but requires a smaller land footprint and contributes minimally to mine tailings in comparison to open-pit mines, with strip ratios less that 0.5:1. Upfront and ongoing costs of these projects are unknown, but expected to be high, and efforts to reduce necessary consumption of fuel, energy, and water, as well as the costs of managing wastes and environmental impacts will support economically viable Cu mine activities.

We caution the use of LCA database factors for representing diesel consumption at individual mines and encourage researchers to identify industry partners that can validate process models of mining operations for bottom-up sector modelling. We conclude by encouraging researchers to attend to key research gaps including outdated and overgeneralized representations of mining activities in market analysis and LCA that will not hold with the advent of the many new Cu producing projects and technologies emerging as a result of the growing demand for domestic copper. For example, increased use of leaching will also raise electricity and water demand, but could allow for the treatment of existing waste stockpiles, reducing diesel consumption and the need for new excavation. When considering the sources of Cu that meet apparent demand for Cu, domestic primary Cu could meet today's demand but imports will be necessary to meet demand projections for 2035. Secondary copper has not played a significant role since the year 2000, but a sharp increase in demand would benefit from appliances and energy related equipment reaching end-of-life, and the opening of new secondary smelters and electrolytic facilities.[8,15]

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