FEATURE ARTICLE

Copper: Mining, Development, and Electrification

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Abstract

To calculate the additional copper required for the electrical transition from fossil fuels to electric energy, we first establish a business-as-usual baseline, assuming continued growth in demand driven by global population growth and rising standard of living. We then project the extra copper needs of the electric transition relative to this baseline. The extra copper that cannot be supplied through recycling must be mined, and we determine the annual increase in mining necessary to support the electrical transition. Our analysis shows that, while there is enough discovered copper with resources close to being defined to meet demand for the next 25 years, the rate at which it needs to be mined poses significant challenges. The unavoidable conflict between the copper demands of electrification and achieving equitable living standards for the developing world underscores the importance of resource-realistic policies. Given that the sharp increase in copper demand is primarily driven by batteries, the extra copper needs for electrification can be significantly reduced if the need for electrical storage is minimized. This can be achieved by generating electricity through a mix of nuclear, wind, and photovoltaics; managing power generation with backup electric plants fueled by methane from abundant resources of natural gas; and transitioning to a predominantly hybrid transportation fleet rather than fully electric vehicles.

Introduction

There is widespread concern in the resource community that necessary minerals and metals may not be available for the electrical transition from fossil fuels to noncarbon energy sources. We focus on copper for several reasons. First, remedying supply shortfalls of copper—which has been explored, mined, and produced for over 120 years in increasingly high tonnages—is likely to be substantially more difficult than increasing the supply of metals like lithium, which has not been previously extensively sought. Second, copper is probably the most essential material next to iron and concrete for development in low-income and middle-income countries. It is essential for transitioning energy generation from fossil fuels to noncarbon sources such as solar and wind and for the use of electric vehicles (EVs) for transportation. Third, a shortfall in copper supply will affect nontransition development and prevent some transition scenarios, making it central to policy considerations. We first define a business-as-usual copper demand baseline that identifies demand trends, excluding vehicle electrification or shifting to noncarbon electricity generation, but capturing demand trends related to population growth and continued global development. We then determine the increase in mining relative to this baseline. We calculate the extra copper mining needed to electrify the global transportation fleet and transition from fossil fuels to various mixes of noncarbon energy sources. If the wind and solar contribution is substantial, supplying the extra copper could impose unrealistic, if not impossible, demands on mining. Our analysis shows that the baseline copper demand is mostly needed by the developing world and that the extra copper required for the noncarbon transition is primarily for batteries. We then outline noncarbon strategies that require minimal additional copper mining, allowing future mining to meet the basic needs of the developing world.

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Defining a Business-as-Usual Copper Demand

Figure 1 plots historical copper mine output in millions of tonnes per year (Mtpy) from 1900 to 2021 (red curve) and projects copper mine output to 2200 using a symmetric logistic growth curve model (blue curve) that accounts for resource depletion. The refinery output curve (black curve above the blue curve) includes the contribution of recycled copper, assuming an annual increase of 0.53% as observed over the last 20 years (Cathles and Simon, 2024), growing from 0.2 in 2018 to 0.35 in 2047. The refinery output curve represents the total usable copper supply. Cathles and Simon (2024) have shown that this refinery output equals the demand projected to 2050 by Yergin et al. (2022). The mine production and refinery output curves are business-as-usual projections, based on trends before 2018. They do not anticipate the new copper demands from electrification and elimination of fossil fuels. Instead, they reflect the current expectation that growth and modernization of the less developed world, along with increased prosperity in the developed world, will continue as they have in the past.

Such predictions work well until conditions change. For example, the mining trajectory of the blue curve in Figure 1 has the same mathematical basis as the petroleum production curve of M. King Hubbert, which successfully predicted the timing of the peak and ensuing decline in U.S. oil production at a similar stage of exponential growth (Deffeyes, 2006). The predicted production trend remained valid until the discovery that hydrocarbons could be produced from shale, essentially a new source not considered by Hubbert in the 1950s. The concepts of peak oil and peak copper have been properly criticized for overlooking technological advances and new resource types (Meinert et al., 2016; Mudd and Jowitt, 2018; Deming, 2023). However, the blue curve is suitable for defining a business-as-usual copper supply scenario. This mathematical projection, based on past recovery history, predicts a resource endowment (6,598 Mt) similar to the USGS estimation (5,600 Mt), which is based on the geologic likelihood of future discoveries

Digital appendices are available in the online Supplements section.

Copper: Mining, Development, and Electrification (*cont.*)

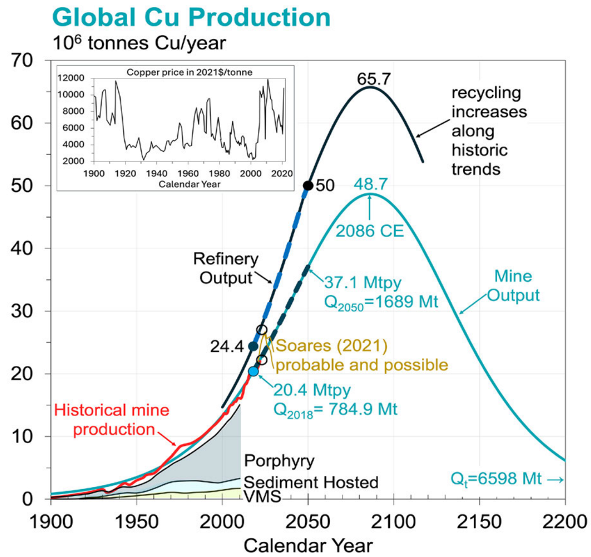

Fig. 1. Projection of past copper mine production and refinery output. Most of the figure is from Cathles and Simon (2024), and full details of its construction are given there. The historical mine production and the deposit types that contributed to production between 1900 and 2001 are taken from Northey et al. (2014). The white gap between the top of the porphyry contribution and the red total mine production curve is the contributions from other mine types. Production from 2000 to 2021 is from the U.S. Geological Survey (www.usgs.gov/centers/national-minerals-information-center/copper-statistics-and-information). The copper price from 1900 to 2021 in constant 2021 dollars is from https://elements.visualcapitalist.com/120-year-perspective-copper-supercycle/ using data from the US Federal Reserve and Roskill. The refinery output (black curve) exceeds the mine output (teal curve) by the recycled copper contribution. The fraction of recycled copper in refinery feed increases from 0.2 in 2018 at 0.53% per year until it reaches 0.35 in 2047, which is considered a practical limit. The open black data points indicate mine and refinery output in 2023. The brown curves show probable and possible future production histories determined from anticipated mine openings and closures by Soares (2021). Abbreviation: VMS = volcanogenic massive sulfide.

in permissive regions (Hammarstrom et al., 2019). The World Copper Factbook 2024 (International Copper Study Group, 2024) breaks down the total copper resource of 5,600 Mt into 1,000 Mt of reserves that we have sufficiently drilled and are confident to be mined, 1,100 Mt of identified resources that could be mined but have not been validated by drilling, and 3,500 Mt of resources that might be discovered in the future. The blue curve adds 1,000 Mt to the undiscovered category. Thus, two thirds of the 6,600 Mt of copper under the blue curve (4,400 Mt) is undiscovered, presenting a significant discovery challenge. It is uncertain whether we will find the undiscovered copper. Nevertheless, the 6,600 Mt copper under the blue curve in Figure 1 serves as a useful reference for expressing the magnitude of the future exploration challenge and the magnitude of future copper extraction. The blue curve itself is helpful in suggesting when we might have to start mining unconventional resources. Trends in deposit type indicate the kinds of deposits likely to contribute to copper supply in the next decades, and the insert suggests the magnitude of expected price variation.

The proposed renewable energy transition spans the relatively short period from 2018 to 2050 (indicated by the black dashed lines overlying portions of the mine and refinery output curves). During this interval, copper demand (refinery output) is projected to increase at 2.2% per year, rising from 24.4 to 50 Mtpy, while mined copper output is expected to grow at 1.9% per year, from 20.4 to 37.1 Mtpy (Fig. 1). The refinery output baseline is a commonly adopted baseline. Watari et al. (2022) use the same baseline and quantify where the business-as-usual copper will be consumed, such as in buildings, consumer electronics, infrastructure, industrial equipment, and transport. On top of this business-as-usual requirement, demand trajectories have been deduced for various scenarios. These include calculating the demand for different levels of vehicle electrification, wind, and solar contributions to electricity generation, and scenarios which favor the market, reduction in greenhouse gas emissions, security of supply control, technological progress, and regional equity. For instance, Watari et al. (2022) calculate that approximately 12 Mtpy of additional copper refinery output will be needed to support the expected growth in the number and types of EVs to 2050, as well as the anticipated increase in the wind and solar contributions to electricity generation by 2050. Such analyses, which do not account for the copper needed to control the variability of wind and solar electricity generation, are reviewed in Appendix 1 ("Uncertainties, parameters and comparisons").

The black dashed portion of the mine production curve shows that mine production nearly doubles, with more copper being mined over the next 32 years than has been mined throughout all of previous human history (905 vs. 784 Mt). Between now and 2050, we are still in the near-exponential growth stage of copper mine output, and we do not yet need to be concerned with the peak and decline of the blue curve related to resource exhaustion. The current concern is not that of the availability of copper to mine, but whether we can discover, develop, and mine deposits fast enough to meet even the business-as-usual demand.

The Business-as-Usual Mining Challenge

The increase in copper mining required to follow the black dashed curve over the blue mine output reference curve from 2018 to 2050 can be estimated. In Figure 1, the 2018 mine output was 20.4 Mtpy, and in 2050, it is projected to be 37.1 Mtpy. The acceleration of mine output over this 32-year period is thus 0.528 Mtpy y^{-1} ([37.1–20.4]/32).

In 2023, copper refinery output was 27 Mtpy, with mining contributing 22.2 Mtpy and recycling 4.8 Mtpy (black open circles in Fig. 1). The mining contribution came from 709 mines. The top 10 producing mines contributed 21% of this production, averaging 0.47 Mtpy each, for a total contribution of 4.72 Mtpy. The 699 smaller mines contributed 15.7 Mtpy, averaging individual contributions of 0.022 Mtpy. To increase mining output by 16.7 Mtpy and reach 37.1 Mtpy by 2050, as suggested in Figure 1, assuming all current mines remain in operation, a combination of the following scenarios must occur: (1) 36 (= 16.7 Mtpy/0.47 Mtpy) new large mines, each producing 0.47 Mtpy, must be operational by 2050; (2) 759 new small mines must be operational by 2050; or (3) the average output of the top ten mines must increase to 2.5 Mtpy from 0.47 Mtpy by 2050. As discussed in the next paragraph, none of these scenarios is likely.

Substantially expanding the output of the largest existing mines is an unlikely option. BHP has reported new investment of up to US$9.8 billion to stabilize copper production at Escondida, the world's top producer, at 1.4 Mtpy until 2030 (2024 production was 1.35 Mtpy). None of the next nine top producers have capacities anywhere close to 2.5 Mtpy. Having 36 new mines producing at 0.47 Mtpy (approximately the production rate of El Teniente in Chile) by 2050 seems improbable, given that first production from a large mine currently occurs more than ~20 years after deposit discovery (Bonakdarpour et al., 2024). This implies that much, if not all, of the future increase in copper mining output must come from the operation of new small mines or from new large brownfield discoveries (discoveries near operating mines), where the development time can be substantially reduced. The challenge will be significant, as few of the currently operating small mines are likely to still be in operation in 2050, and five of the top 10 mines are expected to close by the early 2050s (one prematurely closed in 2024; Wood and van As, 2024). Soares (2021) has estimated probable and possible mine copper output to 2030 based on expected mine openings and closings. Their prediction is shown by the brown curve in Figure 1.

Increasing the rate of mining will require an increase in copper price. Copper capital intensity is a metric for estimating the price increase needed to develop new copper mines. It is the simplest economic measure for deciding whether or not to develop a mine and is universally understood within the mining industry. This metric measures the total cost of development, expressed in U.S. dollars per tonne of copper produced annually, based on an ore reserve estimated following resource definition drilling and used for completing a feasibility study. Capital intensity considers political, financial, and technical risk. Historically, there has been a relatively close relationship between capital intensity and copper price, typically one-to-one. Therefore, present copper capital intensities for mine development can be used to estimate future copper prices.

Based on mines developed in Chile, Wood and van As (2024) demonstrated that copper capital intensity increased threefold between 2001 and 2010, which is comparable to the price increase shown in the insert in Figure 1. Farrell and Whitton (2024) noted that 10 brownfield projects developed in Latin America between 2020 and 2024 had a 2024 capital intensity of US$23,000/tonne. A 2012 unpublished confidential report, seen by the authors and distributed to clients by an international merchant bank, indicates that the top 40 undeveloped copper prospects in the world that year had an estimated 2024 capital intensity of US2024$20,527 (US2012$14,988). These copper capital intensities suggest that the future copper price must exceed $20,000 per tonne for significant new mines to be economically viable and worth putting into production. Given the current copper price of about $9,251 per tonne, this forecasts at least a doubling of copper price will be needed to have any chance of following the black dashed projections in Figure 1.

The Additional Challenge of the Proposed Electrical Transition

The copper demands of an electrical transition away from fossil fuels will require more mining than just meeting the business-as-usual expectations. Figure 2 shows the additional mined copper production needed for this transition. The panels in this figure plot cumulative mined copper as a function of time. The slope represents mine production, while the curvature (the increase in slope over time) during the transition period (in red) and the post-transition period (in green) indicates the new mining required. The figures list the number of large mines (ATTM, average top ten mines) that must be brought into production each year. An ATTM is defined here as a mine with a production of 0.47 Mtpy, which is the average production of the top 10 mines operating today.

The top row of panels repeats the calculations and conclusions of Cathles and Simon (2024). Further discussion is available in that paper. Here, the calculations are for hybrids requiring 40 kg_{Cu} per vehicle rather than 29, and EVs requiring 80 kg_{Cu} per vehicle rather than the 60 kg_{Cu} per vehicle used in Cathles and Simon (2024). Figure 2A shows that to meet business-as-usual copper demand, about one new ATTM must be put into operation each year between 2018 and 2035, and about 1.15 ATTMs per year thereafter. Figure 2B shows that to provide the extra copper needed for the phased-in global manufacture of 100% fully electric vehicles by 2035, a net additional 0.8 ATTMs must be put into operation each year over the transition period from 2018 to 2035. Conversely, Figure 2C shows that phasing in 100% manufacture of hybrids would increase mined copper demand very little.

The bottom row of panels is new and shows the mine development needed to eliminate fossil fuels as well as to manufacture and charge EVs. Figure 2D shows that transitioning to 100% EV manufacture and eliminating all fossil fuels with electricity supplied by 100% offshore wind would require putting into operation 22.5 ATTMs per year between 2018 and 2035, and 2.5 ATTMs per year thereafter. Deposits cannot be discovered and mines cannot be developed at this rate. It is unrealistic to expect that 21 new large mines, each with ~0.5 Mtpy production, can be put into production each year over the next 17 years when it is already challenging to bring one new mine into production each year. Moreover, such an effort, even if possible, would be very wasteful. At the end of the transition, 425 ATTMs would be in operation, up from the 43.2 ATTMs operating in 2018. At the start of the posttransition period, 311 of these would close, as only 114 ATTMs would be needed for continuing growth. By 2050, over half of our total conventional copper endowment above 200 m would have been mined (3,605/6,600 Mt = 0.55). This full electrical transition requires mining twice as much copper as business-as-usual in 2050 (3,605/1,750 Mt).

Figure 2E shows that the increased mining would be 2.4 ATTMs per year (twice the business-as-usual) if only 30% of the noncarbon electricity generation is nonnuclear and the wind and solar variability is controlled by five days' worth of battery storage (almost certainly woefully inadequate; Michaux, 2024b). There would be a substantial drop in mining demand at the end of the transition in 2035.

By contrast, Figure 2F shows that only a small increase in new copper mining above the business-as-usual 1 ATTM per year would be needed if nuclear contributed 90% of the nonfossil electricity, with 1-day battery storage for the 10% wind and solar power contribution. If nuclear contributed 70% of the power and the variability of the 30% contribution from wind and solar were managed by a backup infrastructure of electrical plants fueled with methane, the mined copper required would also be very close to business-as-usual (App. 2 spreadsheet tab 7f3).

The plots in the panels of Figure 2 are calculated using the spreadsheet provided in Appendix 2. The spreadsheet is an integral and important part

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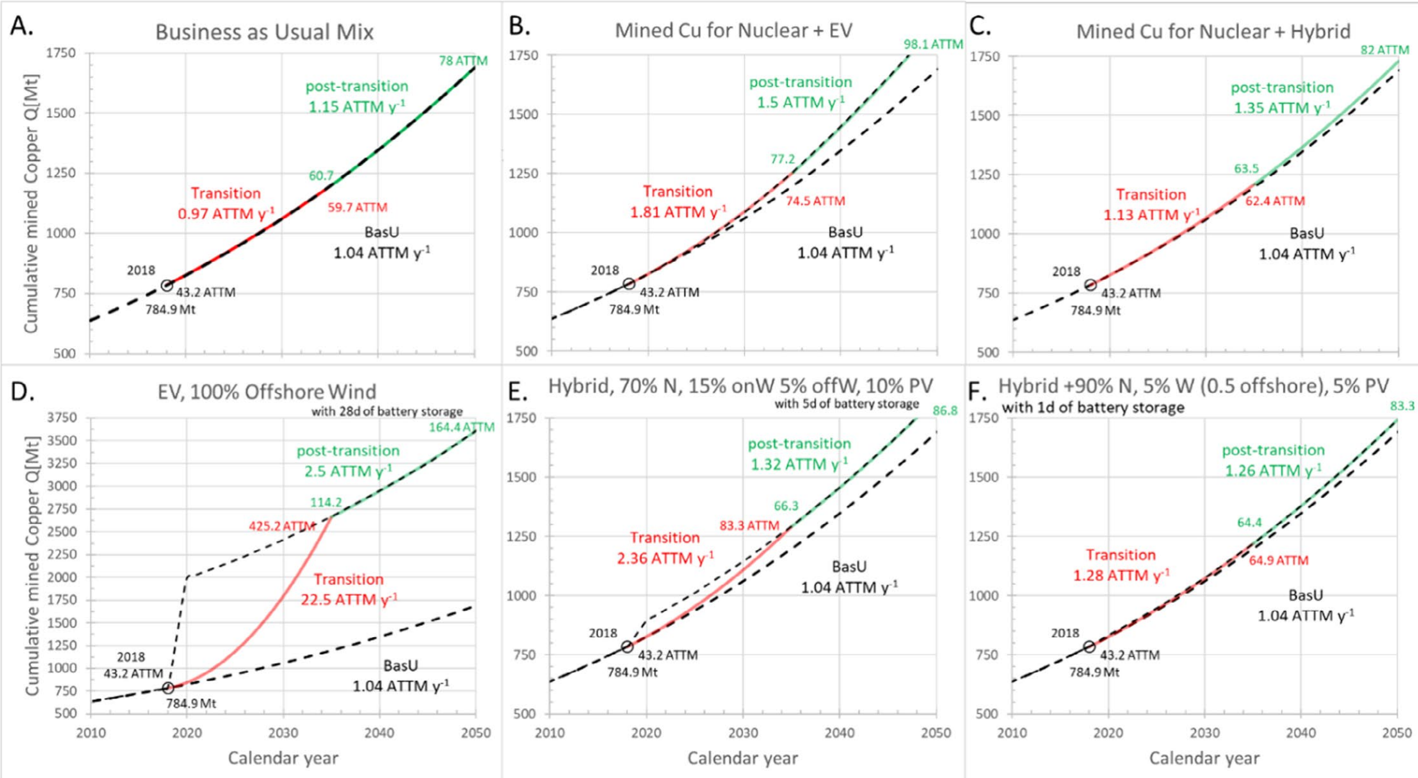


Fig. 2. Cumulative mined copper demand for electrification of the transportation fleet (A-C) and, in addition, for transitioning to nonfossil electricity generation (D-F). The lower black dashed curve shows the cumulative copper supply needed for business-as-usual progress; the top black dashed curve shows the cumulative mined copper supply needed for the transition scenario listed. The red curve shows transition and the green curve the posttransition cumulative mined copper trajectories. Labels indicate the net number of ATTMs (average top 10 mines) that must be put into production each year and the total number of ATTMs in operation in 2018, 2035, and 2050. Abbreviations: EV = electric vehicle, Mt = million tonnes.

of this paper. The spreadsheet methods are documented in Appendix 2 tab0 through tab6. The end member design of the spreadsheet allows for the specification of an arbitrary mix of the electrical power plants that replace fossil fuels and permits changes of the parameters that control the calculations. The parameters used in our calculations are compared with those of other published studies in Appendix 1. Appendix 1 also compares literature scenarios with our replications of them, showing that the agreement between our calculations and those of others is good (±20%). Many more scenarios are calculated in the spreadsheet than are shown in the text, and readers can use the spreadsheet to examine their own scenarios. In addition to the online supplements section, the appendices can be found at https://larrycathles.eas.cornell.edu/.

The spreadsheet analysis shows that the amounts of copper needed to control wind and solar variability (i.e., storage batteries) could constitute a large to very large fraction of the total conventional copper resource endowment of 6,600 Mt. A similar quantity of copper is needed to manage power variability with a regional grid. By contrast, the amount of copper needed for new power plants, EVs, and transmission lines is much smaller than the copper required to manage power variability with batteries or a regional grid, given present technology. A major conclusion is that managing the power variability of wind and solar is the primary demand for copper, and this realization must be taken into consideration in any development scenario.

The Copper Required for Human Development

Copper is fundamental to modernizing developing economies and achieving the United Nations Sustainable Goals. It is essential for infrastructure, including electricity production and electrical grids, clean water distribution and sanitation systems, education and healthcare facilities, and telecommunications networks. The level of development at the country level is described by the human development index (HDI), a composite of (1) life expectancy at birth; (2) years of education of adults after age 5; and (3) gross national income per capita. Values for HDI range from 0 to 1 (UNDP, 2024). Figure 3 shows that HDI is strongly correlated with primary energy use and income. Since energy use is proportional to copper use, this indicates that copper is essential for prosperity and well-being.

In-use copper per capita provides a good measure of a country's development, and trends in copper inventory reveal much about what is happening in a country. Figure 4 shows the amount of copper embedded in various categories of infrastructure in the United States from 1900 to 1999. Copper for infrastructure services, such as wiring for power distribution, telecommunications, and building construction, increased at a nearly constant annual rate throughout the 20th century, although copper embedded in buildings increased at a somewhat slower rate. Copper used for equipment and transportation peaked in 1949 and then declined due to disinvestment in electrically powered rail and public transportation systems. Copper in motor vehicles began to

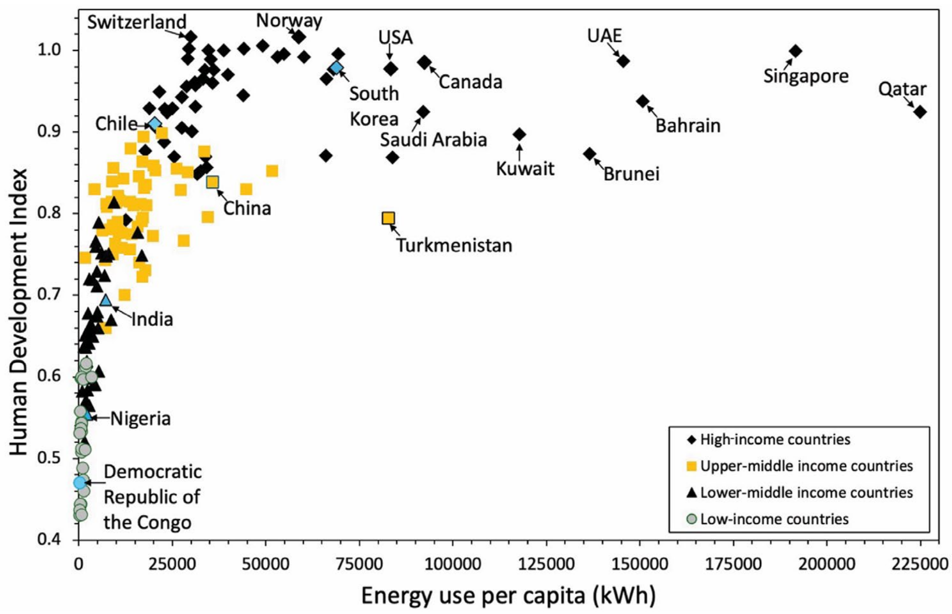


Fig. 3. The relationship between human development index (HDI) and primary energy use per capita for countries categorized by the World Bank using gross national income per capita (GNI) converted to U.S. dollars using purchasing power parity (PPP) rates. Human development index data are from the United Nations Development Programme (UNDP; https://hdr.undp.org/data-center/human-development-index#/indicies/HDI). Primary energy consumption data are from The World Factbook published the U.S. Central Intelligence Agency (https://www.cia.gov/the-world-factbook/field/energy-consumption-per-capita).

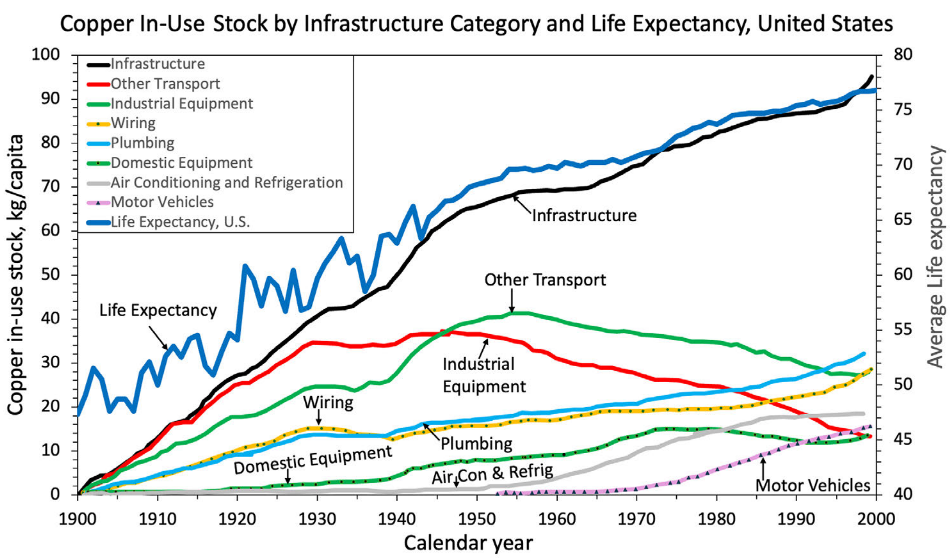


Fig. 4. Copper in-use stock per capita for various infrastructure categories (data from Gordon et al., 2006). Also shown is life expectancy (data from the U.S. National Center for Health Statistics, Centers for Disease Control and Prevention).

increase after 1970, driven by rising per capita vehicle ownership and the increased use of electrically powered auxiliary systems. Copper in industrial equipment increased rapidly from about 1940, due to wartime manufacturing growth and postwar expansion, but declined after 1960 because of deindustrialization. Increased efficiency in copper use caused copper embedded in domestic equipment to decline after 1975.

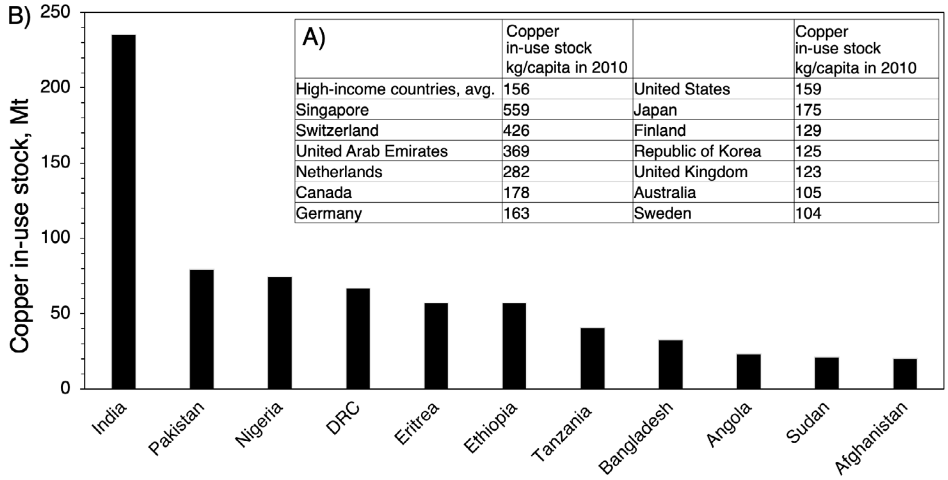
The market growth of air conditioning and enhanced motor vehicle electronics propelled continued growth in per-capita in-use copper stock despite dematerialization and substitution of aluminum for copper wire in high-voltage transmission lines, fiber optic cables for copper wire in telephone systems, and plastic for copper in many plumbing applications. Per-capita use of copper is strongly correlated with life expectancy.

In-use copper stock per capita for high-income countries was estimated to be 156 kg as of 2010 (Watari and Yokoi, 2021). This represents the sum of copper in-use stock for the infrastructure categories shown in Figure 4 (Lifset et al., 2002; Gordon et al., 2006). The black curve in Figure 4 essentially tracks human development in the United States. In 1900, the mean life expectancy in the U.S. for all races and sexes was 47 years, the mean years of schooling for adults was 4.1 years, and purchasing power per capita was about $2,000 in 2024 dollars. Today, U.S. life expectancy is 77.5 years, purchasing power per capita is $75,257 in 2024 U.S. dollars, and over 90% of adults have at least 12 years of schooling.

Less-developed countries are on a similar development trajectory to that of the U.S. Similar growth curves for in-use copper stock describe all high-income member states of the Organization of Economic Cooperation and Development (OECD) and China, along with substantial increases in life expectancy, levels of education, and economic prosperity. In fact, the in-use copper stock of a country's infrastructure provides a good measure of its stage of development and how much copper will be required for that country to reach parity with a developed country.

Figure 5 shows the amounts of copper projected for India and other countries to develop infrastructures equivalent to high-income countries in 2100. India's current per-capita in-use copper stock is about 0.5 kg, which means that India would require 227 Mt Cu for its population of 1.456 billion to reach parity with the U.S., or 235 Mt for the projection of 1.51 billion people in 2100. Together, low-income and lower middle-income countries, including India, will need about 1,043 Mt copper for infrastructure parity with the U.S. and other high-income countries. This is equivalent to about 50 years of current global copper production.

Figure 6 shows that the consumption of refined copper is indeed shifting from the OECD countries to the BRICS (Brazil, Russia, India, China, and South Africa). The consumption of refined copper in OECD countries has remained flat at about 6 kg per person (Gorman and Dzombak, 2019). In contrast, consumption in BRICS countries is accelerating rapidly, increasing from about 0.5 kg per person in 1992 to 2.9 kg per person in 2009. The good news is that the 1,043 Mt of copper needed for India and all low- to middle-income countries to achieve infrastructure parity with the U.S. is only about 16% of the estimated minable resource endowment of 6,598 Mt discussed above (Fig. 1). Furthermore, the 904 Mt of copper that will be mined between 2018 and 2050, according to the business-as-usual trajectory, will be enough to elevate the developing world to 87% copper parity with the U.S., if it is all consumed by developing countries. However, there is an inherent conflict between the copper demands of business-as-usual infrastructure development and human prosperity and the demands for copper to electrify and phase out fossil fuels. Both goals can be met with current technologies if wind and solar are not a significant part of future power generation and hybrid motor vehicles are the dominant choice for transportation electrification. If wind and solar are a significant part of future power generation, and the variability of these sources is managed by battery storage or network averaging, copper will have to be diverted from development uses. Even then, there will not be enough for a nonnuclear fossil fuel transition with no parallel methane power plant network unless additional substitutes for copper are immediately identified and used. Society can have a win-win solution or a fail-fail solution. For a win-win outcome, the copper needs of the electrical transition must be nearly completely eliminated.



	Copper in-use stock kg/capita in 2010		Copper in-use stock kg/capita in 2010
High-income countries, avg.	156	United States	159
Singapore	559	Japan	175
Switzerland	426	Finland	129
United Arab Emirates	369	Republic of Korea	125
Netherlands	282	United Kingdom	123
Canada	178	Australia	105
Germany	163	Sweden	104

Fig. 5. (A) High-income countries' in-use copper stock per capita in 2010. (B) In-use copper stock (million tonnes [Mt]) increase required for representative low-income and lower middle-income countries to reach infrastructure parity with high-income countries (156 kg/capita) in 2100. Data from Watari and Yokoi (2021) and Yokoi et al. (2022). DRC = Democratic Republic of the Congo.

Discussion

The global elimination of fossil fuels by creating an all-electric infrastructure powered by wind and solar will be challenging (e.g., Loáiciga, 2011; Schipper et al., 2018; Gross, 2020; Jacobsen, 2020; Holechek et al., 2022; IEA, 2023; Osaka, 2023). Electricity supply must be reliable to avoid delivery failures (brownouts), and it must operate within a narrow voltage and frequency range to prevent damage to sensitive equipment (Brown, 2009; Michaux, 2024a). Integrating high percentages of variable wind and solar power into a stable electrical grid presents substantial challenges (IEA, 2024). If the electrical power supply is unreliable, variable, or unclean, households and businesses will be forced to purchase protective devices. This is inevitable because so much personal and business value is at stake. These protective devices are likely to involve battery storage, and current batteries contain a significant amount of copper. Therefore, if the power supply is not 100% reliable and of constant voltage and frequency, the demand for copper will increase well beyond the ability of mining to deliver.

Certainly, copper use in batteries can be reduced (this is already occurring), and less copper-intensive methods than batteries or a regional grid might be found to manage power variability. However, such developments would take time to develop, demonstrate, and implement at the required scale, and the reductions in contained copper would need to be very large to be significant. Nuclear electric or a backup infrastructure of methane-fired electrical plants are practical and reliable ways to make a rapid (several-decade) electrical transition and eliminate a large percentage of fossil fuels from electricity generation. Society has experience with both of these power sources and knows how to deploy them. For cost reasons, and in the long term, adopting nuclear as a 90% base of future electrical power generation seems desirable. In the shorter term, managing variability with a parallel network of methane-fired electrical plants, together with manufacturing a high percentage of hybrid (rather than fully electric or plug-in hybrid) motor vehicles, seems a viable way to eliminate the extra copper demand from an electrical non-fossil fuel transition (Fig. 2F).

Avoiding a substantial reduction in mining demand at the end of a transition to noncarbon electricity generation will be important. Investment in exploration and mine development will be discouraged if investors do not foresee steady long-term demand.

Human society is arguably expecting to stay on the business-as-usual mining trajectory, and deviating from this substantially will almost certainly be politically and actually problematic, especially for the developing world. To encourage the necessary mineral exploration, orebody discovery, and mine development, copper prices in the short term will probably have to at least double. Unfortunately, and paradoxically, more expensive copper will likely compromise societal development, especially in low- and middle-income countries. Present public attitudes toward socially and environmentally acceptable mining will have to change if a major increase in copper supply is to occur. This will require an understanding in the developed and developing world of how modern mining differs from historical practices, some of which are unfortunately visibly continuing in artisanal mining. To credibly communicate the crucial necessity of mining to developing countries, the Western world needs to strongly encourage the opening of new mines on their own territories and show how they can be operated in a societally beneficial and environmentally responsible manner.

Conclusions

A noncarbon transition that involves a large contribution from wind and solar electricity generation will require a quantity of copper that is impossible for mine production to meet. This copper demand resides almost entirely in managing power variability. The copper

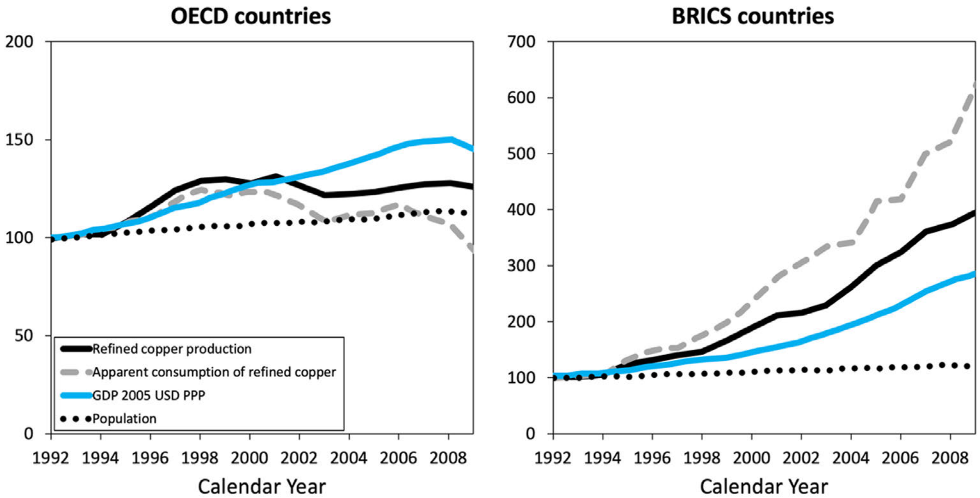


Fig. 6. Shift in refinery consumption from developed to developing world from Organisation for Economic Co-operation and Development (OECD; 2015, fig. 6, p. 127). OECD copper consumption was 7.4 kg/p in 1992 and 6.4 kg/p in 2009. BRICS (Brazil, Russia, India, China, and South Africa) copper consumption was 0.5 kg/p in 1992 and 2.9 kg/p in 2009.

needed for battery storage to manage power variability is enormous, and the copper required for managing the variability with a regional network seems to be equally large. Transition copper demands can be reduced with current technologies by increasing the contribution of steady nuclear electricity generation to the noncarbon power mix or by managing the variability of a larger fraction of wind and solar electricity generation with a backup infrastructure of methane-fired power plants. Transition copper demand can be further reduced by growing a dominantly hybrid transportation fleet. These copper reductions will leave more future copper production available for the development of the developing world.

The copper mining challenge associated with reducing fossil-fuel electricity generation is severe, and ensuring a stable electricity supply will require resource-realistic policies. A spreadsheet provided with this article can be useful in identifying mining-realistic policies. The spreadsheet can flexibly evaluate the mining needs of any mix of electrical power plant types, vehicle electrification styles, and methods of power variability control.

Conflict of Interest

The authors declare no conflicts of interest.

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