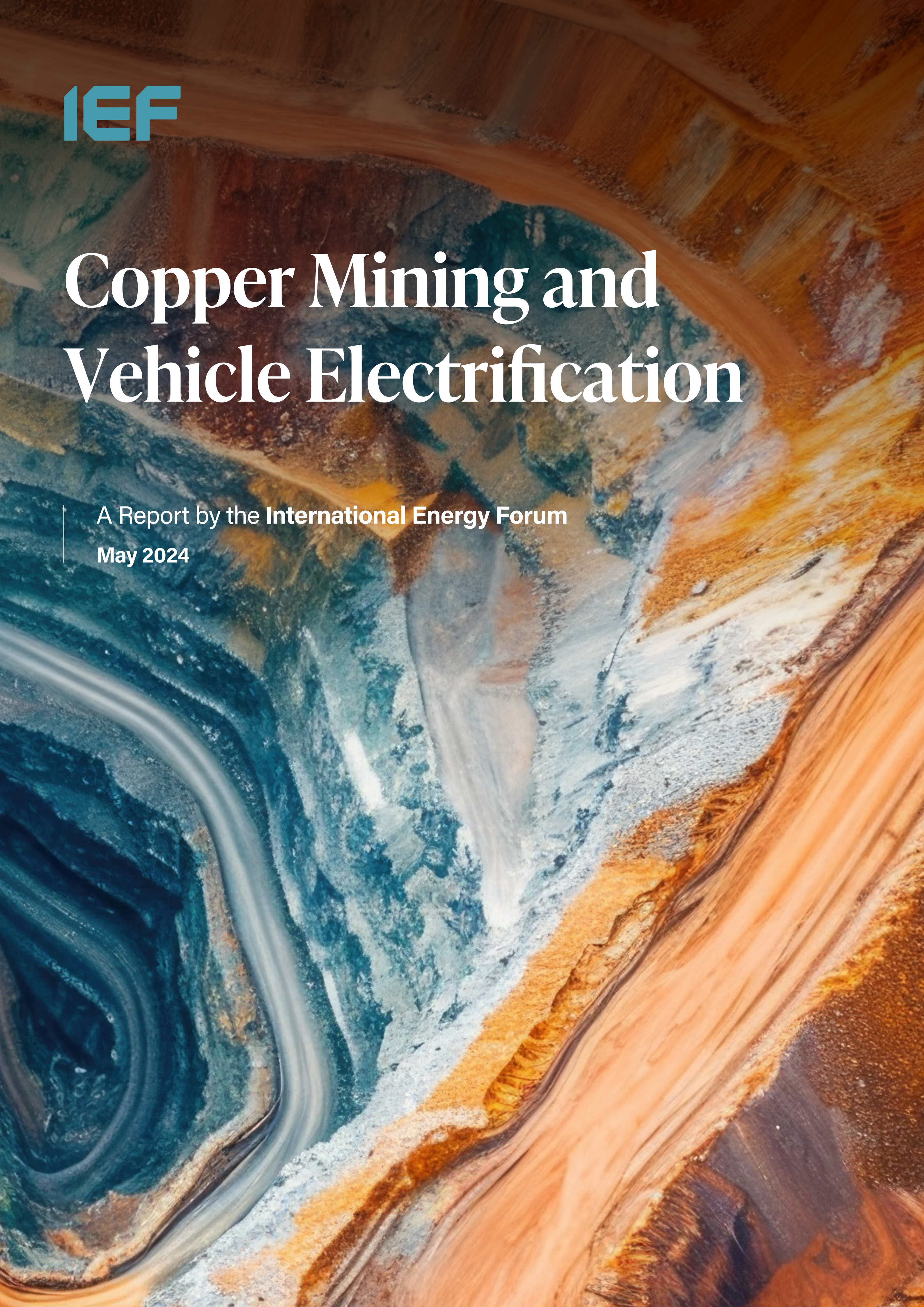

Copper Mining and Vehicle Electrification

A Report by the **International Energy Forum**

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INTERNATIONAL
ENERGY
FORUM

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Biography

After doctoral research on the viscosity of the earth's mantle at Princeton University, Cathles spent periods at Kennecott Copper Corporation's Ledgemont Laboratory, The Pennsylvania State University, and the Chevron Oil Field Research Laboratory before joining the faculty of Cornell University in 1986 and becoming professor emeritus in 2018. Larry co-directed the Global Basins Research Network, was the 24th Hugh Exton McKinstry Memorial Lecturer (1989) at Harvard, and the 2008 Adrian Smith Lecturer at the University of Waterloo. He was the 2011 Distinguished Lecturer and the 2021 Penrose Gold Medal recipient of the Society of Economic Geologists and is a fellow of the American Association of the Advancement of Science. He was a leader of the oil and gas thrust of the Cornell KAUST program, and a Director of Cornell's Institute for the Study of the Continents. He has published over 140 peer-reviewed publications and a book: "The Viscosity or the Earth's Mantle".

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Biography

Adam is Arthur F. Thurnau Professor of Earth & Environmental Sciences at the University of Michigan and a Fellow of the Society of Economic Geologists. His research focuses on the geology and geochemistry of mineral deposits that provide society with copper and other critical minerals. Adam has led research programs on all seven continents. He has co-authored the textbooks Mineral Resources, Economics and the Environment, which is considered an authoritative source for beginners and experts, and Earth Materials: Components of a Diverse Planet. He has published 100 peer-reviewed research articles and has received awards for his transformative approaches to education including the University of Michigan Teaching Innovation Prize and the Distinguished Teaching Professor from the University of Nevada Las Vegas. He regularly delivers lectures to the general public and experts on all aspects of the energy transition including a TEDx talk. He is the 2024 Society of Economic Geologists Distinguished Lecturer.

About the International Energy Forum

The International Energy Forum (IEF) is the world's largest international organization of energy ministers from 73 countries and includes both producing and consuming nations. The IEF has a broad mandate to examine all energy issues, including oil and gas, clean and renewable energy, sustainability, energy transitions and new technologies, data transparency, and energy access. Through the Forum and its associated events, officials, industry executives, and other experts engage in a dialogue of increasing importance to global energy security and sustainability.

Abstract

Electric vehicles (EVs) require substantially more copper and other metals than conventional internal combustion engine (ICE) vehicles. For example, manufacture of an ICE automobile requires 24 kg copper whereas manufacture of an EV requires 60 kg. Many have expressed concern that the lack of critical mineral resources may not allow full electrification of the global vehicle transportation fleet, and the vehicle electrification resource demand is just a small part of that needed for the transition. By displaying both demand and mine production in full historical context we show that copper resources are available, but 100% manufacture of EVs by 2035 requires unprecedented rates of mine production. The 100% EV target not only requires significant extra copper for battery manufacture, but also more copper for grid upgrades to support charging, while hybrid electric vehicles do not require extra grid capacity. Under today's policy settings for copper mining, it is highly unlikely that there will be sufficient additional new mines to achieve 100% EV by 2035. Policymakers might consider changing the vehicle electrification goal from 100% EV to 100% hybrid manufacture by 2035. This would allow for future output of existing and new copper mines to be used for the developing world to catch up with the developed world in electrification. Life cycle emissions for battery electric vehicles compared with hybrid electric vehicles are comparable with each other. Mining must be recognized as essential, and exploration and responsible copper mine development strongly encouraged.

Significance Statement

Climate policies presently assume that the materials required to transition to zero carbon emissions will be available, but this need not automatically be the case. The message that we may not be able to mine materials fast enough to meet humanity's desires even if there are more than enough of these materials to meet all of humanity's needs has proven difficult to effectively deliver, yet its effective delivery and subsequent discussion is necessary to the formulation of realistic energy resource policies. We hope that by presenting future copper mining requirements in a single comprehensive diagram that is concisely supported by all relevant methods and data will prove helpful in understanding and managing the material resource challenges that lie ahead.

Introduction

Copper is the mineral most fundamental to the human future because it is essential to electricity generation, distribution, and storage. Copper availability and demand determine the rate of electrification, which is the foundation of current climate policy[7]. Many studies have raised concerns that copper supply cannot meet the copper demands of both the green energy transition and equitable global development[1-15], but the seemingly universal presumption persists that the copper needed for the green transition will somehow be available. This need not be the case for even the first step of vehicle electrification. This paper addresses this issue by projecting copper supply and demand from 2018 to 2050 and placing both in the historical context of copper mine output. Discussion is focused on a single diagram that illustrates the unprecedented nature of the copper mining challenge and ways to reduce copper demand. Just to meet business-as-usual trends, 115% more copper must be mined in the next 30 years than has been mined historically until now. To electrify the global vehicle fleet requires bringing into production 55% more new mines than would otherwise be needed. On the other hand, hybrid electric vehicle manufacture would require negligible extra copper mining. The figure summarizes projections of both demand and supply in a fashion that has not been done before and we discuss aspects of copper exploration that have not seen much discussion. Our main purpose, however, is to communicate the magnitude of the copper mining challenge to the broader public that is less familiar with upstream resource issues. To this end, the discussion is brief, non-technical, and focused on a single metal, diagram, and issue (vehicle electrification). All relevant methods and data are concisely provided in supplemental material. We hope this will promote discussion and formulation of alternative policies to be certain the developing world can catch up with the developed world while global initiatives advance with the green energy transition.

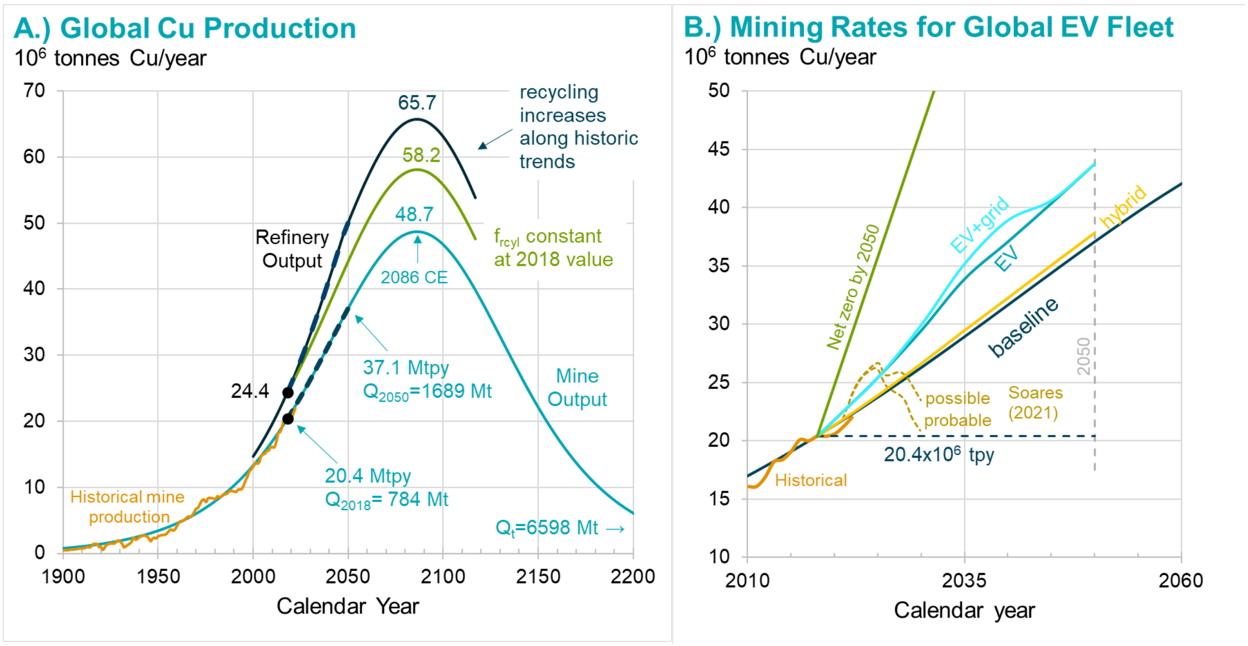

Figure 1. *(A) Historic and projected mined copper production (orange and teal-colored curves). The refinery output that includes recycling and equals the copper supply is shown by the dark blue curve and green curve. The green curve assumes a recycling rate equal to that in 2018. The dark blue solid curve assumes recycling rate increases along the trends of the past 20 years to 2050 and then is constant.* Q_{date} *indicates the tonnes of copper mined up to a particular date and equals the area under the teal curve up to that date. The copper production rates (mine or refinery) are also shown.* Q_t *at the bottom right is the estimated total minable copper resource. (B) Curves showing the copper mine production required to: (1) Meet business-as-usual (non-energy transition purposes) demand[5] (solid dark blue baseline). (2) Meet BasU demand and convert the global vehicle fleet to hybrid electric vehicles (yellow hybrid line just above the dark blue baseline). (3) Meet BasU demand and convert the global vehicle fleet to battery electric vehicles (teal EV curve) and upgrading electricity and transmission (light blue EV+grid). (4) Supply the copper needed to transition to net zero* CO_2 *emissions (wind and solar rather than fossil fuels) by 2050 (green line). (Panel curves calculated and plotted in SM4 tabs 1 and 5.)*

Copper mining and refining

Mining and refining

Figure 1A shows the historical mine production[10] and projects future mine production based on it (teal curve) using methods described in SM1. Those methods assume that the copper resource currently being tapped is finite, and that neither the nature of the resource or the methods of its exploration and extraction change significantly over the next 30 years (the projection period). The methods are the same as M. King Hubbert successfully used to predict ~30 years of U.S. oil production right up to when technologies such as directional drilling and hydraulic fracturing made it possible to produce natural gas and crude oil from shale and expanded the hydrocarbon resource. Since technologies can change, the teal curve should be considered an expected reference against which departures can be detected. It predicts that mine output will peak at 48.7 Mtpy in 2086 and then decline. It is a trajectory very similar to that deduced by very different methods (assessing the rates of copper mining likely in favorable geographic regions)[17].

The dark blue and green curves are two projections of refinery output (copper supply), calculated by projecting historical trends in the ratio of refinery to mine output (SM1). Refinery output is greater than the mine output because copper recycling is an additional refinery input. Heavy black dashes indicate the portions of the refinery and mine output curves that lie between 2018 and 2050. These curves identify the copper mine output and copper supply (refinery output) that is expected if the world proceeds as it has since ~1900. These trends do not include the copper demands of the green energy transition and we refer to them as business-as-usual trends or baseline curves. They show an almost linear increase in mine production and refinery output over the 32 years (2018 to 2050) that extends recent trends. They are not sensitive to uncertainties in the data that define the full mine output curve (see Figure SM1.2).

It is shown in SM2 that the sum of copper demand from the global manufacture of ICE vehicles, historic trends in global grid improvement, and other increases in copper demand that are not related to the green energy transition is nearly coincident with the projected refinery output (see Figure SM2.4). These two projections need not be equal. The fact that they are equal increases confidence in both and means the mining baseline is a valid demand baseline (added discussion is in SM1). The dark blue baseline curve in Figure 1B can therefore be taken to equal the business-as-usual mined copper demand shown in Figure 1A. The copper mine production required to support successive steps of the green transition are displayed above this business-as-usual mining demand baseline. For example, the gap between the yellow and dark blue lines indicates the additional mine production needed to globally manufacture hybrid rather than ICE vehicles. The gap between the teal and dark blue curves indicates the additional production needed for 100% EV manufacture by 2035. The light blue EV+grid curve indicates the additional copper production needed for the grid improvements that charge the EV fleet. The green net zero by 2050 curve indicates the extremely large additional copper mining rates required to replace all fossil fuel energy sources by renewable energy sources by 2050.

New mines to meet future demand

The rate at which new mines must be opened to support the copper mine production shown in Figure 1B can be deduced from these curves. Assuming for the moment that the mines in operation in 2018 continue to produce at the same rates until 2050, new mines must supply the mass of copper represented by the area between the curves and the dashed dark blue horizontal extension of 2018 production underlying them. The first column of Table 1 lists these masses. The second column lists the mine production in 2050 that is required to supply the added copper. Because the mining demand increases linearly, the mining rate needed in 2050 equals twice the average mining rate over 32 years from 2018 to 2050. For example, the 260 Mt of mined copper needed to meet the business-as-usual demand requires an average mine output of 8.13 Mtpy over 32 years, and therefore production from new mines (i.e., mines put into operation after 2018) of 16.3 Mtpy in 2050. The next column lists the number of new mines with production rates of 0.472 Mtpy (the average production of the top 10 mines in operation today) that must be in operation in 2050, and the last column indicates how many such mines must be discovered, permitted, and put into operation each year between 2018 and 2050. New copper supply will come mostly from large mines because they are the ones that count in terms of total production[9]. Table 1 shows that to remain on the baseline and support the green transition, between 35 and 194 large new mines must be brought into production over the next 32 years at a rate of between 1.1 and 6 mines per year.

Table 1. Extra copper (relative to 2018) mined between 2018 and 2050 and number of mines that must be put into operation each year over this period to meet electrification demands (see SM4 tab 5).

	Mt mined above 2018 line	*New mine production in 2050 in Mtpy*	*New mines* in 2050*	*New mines* per year*
baseline	260	16.3	35	1.1
Hybrid	275	17.2	37	1.2
EV+grid	404	25.2	54	1.7
net zero	1460†	91.3	194	6.0

†Assumes that net zero requires mining 1200 Mt additional (above baseline) copper[13,14]*. Mines* indicates the number new mines with a production rate of 0.472 Mtpy, the average production rate of the top 10 mines producing today (SM3.2).*

The departure from baseline to meet the EV manufacturing goal will be unprecedented

Figure 1 shows that meeting the goal of 100% EV manufacture by 2035 will require an unprecedented departure from the copper mining baseline. Historically, excursions from mine production have been ~1 Mtpy in magnitude over about ~15 years (less in recent times, see Figure 1A). Actual copper production tracks the baseline remarkably closely because powerful economic incentives correct departures. If there is too little copper production relative to demand, the price of copper rises and greater production is encouraged. If too much copper is produced relative to demand, the price falls and mines close or halt operation. The price/production feedback means that it is hard to depart from the baseline (see SM1). Figure 1B shows that the departure from the baseline related to EV manufacture will be five times greater and twice as long as we have experienced before (>5 Mtpy for >30 years). Corrected for recycling, this mining excursion is equivalent to a demand gap of 8.1 Mtpy in 2035 and 9.6 Mtpy in 2040. A predicted supply-demand gap of >9Mtpy[5] by 2035 is in good agreement with the data reported here.

Discussion

The most immediately evident and important feature in Figure 1 is its prediction of a significant increase in required copper mining between 2018 and 2050. Over this 32-year period the world will need to mine 115% more copper than has been mined in all of human history up to 2018 (905 compared to 757 Mt). Copper mine output will increase by 82% (from 20.4 to 37.1 Mtpy), and many new mines will open. The reason for this large increase in mining activity is largely to support the developing world. In 2022, 74% of copper refinery output was consumed by Asia, only 23% in the U.S. and E.U. Copper's ability to conduct heat and electricity, its ease of fabrication, its corrosion resistance, and its relatively low cost make it essential and attractive to use in many kinds of appliances, heating and cooling systems, telecommunications, motors, wiring, radiators, and other uses that are fundamental to economic development. Three quarters of refinery copper is used in electrical devices, ¾ is sold as wire or tube, and ¾ is sold to the countries currently undergoing the most rapid development.[16] The future output of existing and new copper mines is mostly needed for the developing world to catch up with the developed world.

It is natural that such a large increase in mining activity should raise anxieties of many kinds. Are the resources there to support such a dramatic increase in mining? What practices are needed to ensure mining is done in an environmentally sustainable way? How will the mines affect neighboring communities? Can the underdeveloped world develop without massive mine expansion? Much has been written about these anxieties, but all are logical consequences of the dramatic increases in copper mining predicted by the teal mining baseline curve in Figure 1A.

The most evident feature of Figure 1B is its indication that the copper needed to shift from ICE to EV production will require ~55% more new mines than baseline. The area between the light blue “EV+grid” and the dark blue “baseline” curves is 55% of the area between the baseline curve and the dark blue dashed extension of 2018 production (see also Table 1).More copper is needed for EV-related grid upgrades. The new copper mining needed to replace fossil fuel by renewable energy sources is 4.6 times the baseline (=1200 Mt/260 Mt). The substantial (EV transition) to almost unimaginably large (for net zero emissions) copper mining demands of these green transitions pathways raises other very logical questions, such as whether there are ways the copper needed might be reduced, or copper might be mined more quickly?

Managing the copper demands of electrification and the transition to renewable energy sources may be necessary, and many are working on this challenge. The question is how much copper will be available when it is needed. Spreadsheets for all the calculations and figures in this paper are provided in SM4, and the amounts of copper we assume can be easily modified. We doubt, however, that reasonable reductions will change the discussion below substantially.

The first point related to copper mining that we would make is that there is plenty of copper available. The 1689 Mt of copper that the teal baseline curve in Figure 1 suggests will be mined by 2050 represents 26% of the total copper resource of 6598 Mt. (The USGS[17] estimate of 5600 Mt of copper in undiscovered porphyry and sediment-hosted deposits alone is very close to this estimate.) If mining shifts to greater depths in Earth's crust, the copper resource grows to 89,000 Mt[18], and 241,000 Mt may be recoverable from the seafloor[19]. There is plenty of copper available.[20]

The concern is that we may not be able to mine the copper resource fast enough to support baseline global development and vehicle electrification. The strongest evidence for this concern is the lack of sufficient copper resources in the discovery pipeline. New copper mines that started operation between 2019 and 2022 took an average of 23 years from the time of a resource discovery for mines to be permitted, built, and put into operation[5]. Within this long discovery-to-operation pipeline, we should see at least ten years of prospects (e.g., 17 prospects) with a combined production potential of >8 Mtpy in the pipeline to have any confidence we can meet the 1.7 major deposits per year discovery rate required for EV manufacture. There are not the needed prospects in the pipeline. A detailed study of scheduled mine closures and new mines developing from prospects in known stages of permitting[24] indicates copper mining between 2021 and 2030 will follow the brown-yellow dashed curves in Figure 1B. Production will increase above baseline until 2025, but then strongly decline such that mine production rates in 2030 are nearly the same as in 2018. Others confirm these suggestions[21,22].

Mining companies are struggling to discover new large high-grade copper deposits[11,23,24]. Only 16 of the 224 copper deposits discovered since 1990 were discovered in the past decade, despite mining exploration budgets that increased by a factor of three to four since 2005[5,25]. Discovery requires that vast amounts of land be open to exploration[17], and land access is increasingly difficult. Discovery is a chain of tough probabilities. Discovery of a copper occurrence must be followed by drilling and preliminary economic and engineering assessment to confirm a potential mineral resource. Further drilling, economic evaluation, engineering, and metallurgical assessment are required to develop an ore reserve that can serve as the basis for building a mining operation. In the period between 2001 to 2010, about 20 new copper deposits of at least 0.1 Mt were discovered per year. From 2015 to 2022 this decreased to less than 10 per year. The success rate of discovering an initial occurrence of at least 0.1 Mt was around 1 in 2500 for the period 2001 to 2010 and is now about 1 in 5000. This is for the initial discovery. The rate of success for a copper occurrence becoming an economic deposit that can be mined is between 1 in 100 and 1 in 800[25]. Compounding these increasingly severe discovery challenges is the unpopularity of mining in many localities. Significant copper resources have been discovered but after many years of effort mine permit applications have been canceled in Alaska[26,27], Minnesota[28] and Panama[29], delayed in Arizona[30,32], and substantial acreage has been removed from exploration in Minnesota[31]. For example, the underground Resolution copper project in Arizona would be the largest in North America, producing ~0.5 Mtpy but despite being approved in 2014 by the U.S. Congress has still not received approval to start producing copper[33]. There is thus reason for concern that, under the challenges of discovering ever more copper, production will drop substantially below the baseline curve.

On the other hand, there are reasons for optimism that we will manage to stay on the baseline curve and be able to respond to some increased demand. In contrast to greenfield mine development, brownfield expansions at existing mine sites is more efficient and current mine sites in Arizona, New Mexico and Utah have substantial copper resources to be developed. With the right macro-economic conditions including a higher copper price, there are also copper resources that lie at depths deeper than the ~500 meters below surface that are currently being explored. Deeper underground mining is feasible by block caving and remote operation methods that are safe and environmentally friendly can be used to develop these copper resources. Deep mines will have a much smaller surface environmental imprint than current surface mines. If we begin to explore for deeper deposits, discovery rates could increase. Also, there are substantial copper resources contained in surface stockpiles. For example, Freeport-McMoRan estimates they have over 17 million tonnes of copper in waste stockpiles previously thought to be unrecoverable[34]. With advancements in leaching techniques, they are expecting to extract this copper at the rate of 90,000 tpy which is 20% of the copper production our reference mine. Because it was previously mined, the production is low-cost, demands less water, and has a lower carbon footprint. There are thus reasons to think we could continue to track the teal empirical baseline copper production curve in Figure 1A.

If we do succeed in the discovery and mine creation challenge, the copper needed for business-as-usual trajectory will be provided subject to one additional condition: that our empirical projection of increasing copper recycling is correct. If copper recycling remains constant at its 2018 level rather than increasing as assumed, the refinery output will be 5.7 Mt less (green rather than the dark blue curve in Figure 1A), requiring mine output to increase by 3.7 Mtpy and the discovery and operation of 8 additional mines with productions that average 0.472 Mtpy. The total number of new mines needed to meet baseline demand would then be 43 rather than 35. The need to make up for mine closures and decreased production in mines operating in 2018 will certainly require the discovery and operation of additional mines. We have been optimistic in our projected new mine creation needs.

There is much more that could be reviewed regarding the challenges faced by mining, but the above discussion is sufficient for our current purposes. It highlights valid concerns that we may have difficulty remaining on the business-as-usual copper mine production curve that we have followed for the last ~120 years, and that the amounts of additional copper needed to take even the first step of a green transition (manufacturing 100% EV rather than ICE vehicles by 2035) will require substantial additional mining. The dramatic increase in mining that is needed for business-as-usual developments will raise environmental and social concerns. The important policy goals of globally aligning levels of prosperity, responding to climate change, and managing environmental and local impacts of mine development conflict with one another. Copper demand for EV manufacture could increase the price of copper very substantially and significantly impede the advance of less developed areas.

Recommendations

For the reasons presented above, it is evident that attention needs to be paid to managing the copper demands of electrification and the transition to renewable energy sources. An aspect of Figure 1B not yet emphasized is that there is remarkably little difference between the amount of copper needed to manufacture hybrid electric rather than ICE vehicles. Hybrid electric vehicles require 29kg of copper compared to 24kg for an ICE vehicle. It would therefore be judicious to aim for a transition to the 100% manufacture of hybrid electric vehicles by 2035, rather than transitioning to the 100% manufacture of battery electric vehicles, which require 60kg. The copper required for this transition is only slightly above baseline and does not require major grid improvements (Figure 1B and Table 1). Hybrid electric vehicles could have almost as large an impact on reducing CO_2 emissions and city pollution, and the likelihood of the copper required for their manufacture being available is much greater. Life cycle emissions for battery electric vehicles compared with hybrid electric vehicles are comparable with each other[35], with some variations depending on the model of vehicle. This is not a perfect solution, but it is a much more resource realistic one. Reducing the critical minerals in large battery banks should continue to be sought. Sustainable recycling should be strongly encouraged. Mining could meet a steady copper demand pull with environmentally sustainable mining practices, but mining might not be able to meet too sudden and substantial demand increase and the economic and human welfare consequences of this failure could be substantial.

For the longer term, it is important that copper exploration and mine development be encouraged, starting now. The EU and US should demonstrate on their own territories that increasingly responsible mining can be carried out and thereby prove that they consider mining to be important and are willing to do their share of it. The technologies needed for exploration for deeper copper deposits and leaching should be encouraged as a matter of urgency. To find new mines, vast amounts of land must be available for exploration. Attitudes toward exploration, land access, and drilling must change. Capital allocation for deeper-than-conventional mines or mines in remote locations that lack infrastructure must be encouraged. We should accelerate serious studies of ocean mining with a goal of achieving a scientific understanding of potential impacts by a defined future date. Copper mine output should be compared to the teal baseline curve in Figure 1A in an ongoing fashion and any departures investigated to determine their causes and possible remedies. The ratio of copper refinery to copper mine output should be tracked, and copper recycling encouraged.

We must keep in mind the unique contributions copper makes to modern societal infrastructures and that copper production could peak only ~62 years from now. There is a lot at stake. We hope that Figure 1 and its brief discussion in this paper will help those that are not resource experts appreciate the resource challenge and that this will encourage the discussion and crafting of resource-realistic policies.

Data Availability

All data, methods, and spreadsheets used are provided in Supplemental Material.

References

1. IEA. The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris (2022) https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, License: CC BY 4.0
2. Deetman, S., Pauliuk, S. van Vuuren, D.T., van der Voet, E. & Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances, *Env. Sci. Tech.* **52**, 4950-4959 (2018) DOI: 10.1021/acs.est.7b05549
3. Henckens, L.C.M. & Worrel, E. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *J. Clean Prod* **264** 121460 (2020)
4. Jowitt, S.M., Mudd, G.M. & Thompson, J.F.H. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Commun Earth Environ* **1**, 13 (2020). https://doi.org/10.1038/s43247-020-0011-0
5. Yergin, D., Hoffman, F., Mothersole, J., Rajan, K. & Bonakdarpour, M. The Future of Copper: Will the looming supply gap short-circuit the energy transition? S&P Global Market Intelligence. (2022)
6. Schipper, B.W., Lin, H-C., Meloni, M.A., Wansleeben, K., Jeijungs, R. & van der Voet, E. Estimating global copper demand until 2100 with regression and stock dynamics. *Resour Conserv Recyc* **132**, 28-36 (2018)
7. Larson, E., Greig, C., Jenkins, J. E. et al. Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report, Princeton University, Princeton, NJ, 29 October 2021. (2021)
8. DOE Notice of Final Determination on 2023 DOE Critical Materials List. https://www.energy.gov/sites/default/files/2023-07/preprint-frn-2023-critical-materials-list.pdf (2023)
9. Kesler, S.E. & Simon, A.C. Mineral Resources, Economics, and the Environment. Cambridge Press. (2015)
10. Mudd, G.M. & Jowitt, S.M. Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. Economic Geology, **113**, 1235–1267. (2018)
11. Jowitt, S.M. 30 May 2022, Minerals for future low- and zero-CO energy and transport technologies from: Routledge Handbook of the Extractive Industries and Sustainable

Development Routledge Accessed on: 06 Oct 2023 https://www.routledgehandbooks.com/doi/10.4324/9781003001317-13 (2022)

12. U.S. Geological Survey, 2023, Mineral commodity summaries 2023: U.S. Geological Survey, 210 p., https://doi.org/10.3133/mcs2023 (2023)
13. Henckens, L.C.M., The energy transition and energy equity: A compatible combination? Sustainability (Switzerland) **14(8)** 4781 (2022)
14. Harmsen, J.H.M, Roes, A.L. & Patel, M.K. The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. *Energy* **50**, 62-73 (2013)
15. Michaux, S.P. The Mining of Minerals and the Limits to Growth. Geological Survey of Finland: Espoo, Finland. (2021)
16. https://www.statista.com/statistics/1180230/refined-copper-consumption-distribution-by-world-region/; https://www.statista.com/statistics/1180239/global-copper-semis-first-use-share-by-type/; https://www.statista.com/statistics/693466/distribution-of-global-refined-copper-consumption-by-region/; https://pubs.usgs.gov/fs/2009/3031/FS2009-3031.pdf
17. Hammarstrom, J.M., Zientek, M.L., Parks, H.L. Dicken, C.L., and the U.S. Geological Survey Global Copper Mineral Resource Assessment Team, 2019, Assessment of undiscovered copper resources of the world, 2015 (ver. 1.2, December 2021): U.S. Geological Survey Scientific Investigations Report 2018–5160, 619 p. (including 3 chap., 3 app., glossary, and atlas of 236 page-size pls.), https://doi.org/10.3133/sir20185160. (2019)
18. Kesler, S.E. & Wilkinson, B.H. Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. *Geology*, **36**, 255-258 (2008)
19. Cathles, LM Assessing the greenhouse impact of natural gas, Geochemistry Geophysics Geosystems, **13(6)**, doi: 10.1029/2012GC004032, (2012)
20. Arndt, N. T. *et al.* Future Global Mineral Resources. *Geochem. Persp.* 1–171 (2017)
21. International Copper Study Group. Copper Market Forecast 2023/2024 (2023)
22. Kahn, Y. Copper shortage threatens green transition, Wall Street Journal April 18, 2023, https://www.wsj.com/articles/copper-shortage-threatens-green-transition-620df1e5 (2023)
23. Mills, R. New coper supply offset by multiple hits to existing operations, The Northern Miner, June 19,2023, https://www.mining.com/new-copper-supply-offset-by-multiple-hits-to-existing-operations/. (2023)
24. Soares, A. Copper project pipeline- Project shortage to see supply lag demand post 2025, S&P Global Market Intelligence blog, https://www.spglobal.com/marketintelligence/en/news-insights/blog/copper-project-pipeline-project-shortage-to-see-supply-lag-demand-post-2025. (2021)
25. Schodde, R. Independent technical report on the available global drilling market. https://minexconsulting.com/wp-content/uploads/2022/08/Expert-Report-for-Orexplore-Prospectus-Oct-2021.pdf (2021)
26. Reynolds, J. EPA Blocks Pebble Mine with Rare Veto. What Happens Next? NRDC, January 31 2023, https://www.nrdc.org/bio/joel-reynolds/epa-blocks-pebble-mine-rare-veto-what-happens-

next#:~:text=On%20January%2030%2C%202023%2C%20after,of%20stakeholders%20in%20the%20region. (2023)

27. Bohrer, B & Whittle, P. Alaska gold, copper mine blocked over environmental worries, AP. January 31, 2023. https://apnews.com/article/politics-us-environmental-protection-agency-alaska-business-fish-139ceb6e697c006737d09f984456b0e1. (2023)
28. Institute for Energy Research. Biden Revokes Permit for the New Range Copper Nickel Mine. June 12, 2023. https://www.instituteforenergyresearch.org/regulation/biden-revokes-permit-for-the-newrange-copper-nickel-mine/
29. Moreno, E. First Quantum's Panama mine closure to cost around $800m, minister says. March 12, 2024. https://www.mining.com/web/closure-of-first-quantums-panama-mine-seen-around-800m-minister-says/
30. Haselgrove, S. Rio Tinto, BHP awaiting permits for US copper project, January 18, 2021, https://www.australianmining.com.au/rio-tinto-bhp-awaiting-permits-for-us-copper-project/. (2021)
31. The Hill. Biden administration announces restrictions on hardrock mining in 225,000 acres of Minnesota. https://thehill.com/policy/energy-environment/3831839-biden-administration-announces-restrictions-on-hardrock-mining-in-225000-acres-of-Minnesota-wildernes / (2023)
32. Northey, H. Biden admin hits pause on Ariz. copper mine, May 22, 2023, https://www.eenews.net/articles/biden-admin-hits-pause-on-ariz-copper-mine/.(2023)
33. Institute for Energy Research. An Expected Surplus of Copper has Suddenly Disappeared. December 14, 2023. https://www.instituteforenergyresearch.org/international-issues/an-expected-surplus-of-copper-has-suddenly-disappeared/
34. Freeport-McMoRan Inc. (FCX), 2022, 2022 Annual Report on Sustainability. Available online: https://www.fcx.com/sites/fcx/files/documents/sustainability/2022-annual-report-on-sustainability.pdf-
35. American Council for an Energy-Efficient Economy. Available online: https://www.aceee.org/press-release/2024/02/electric-vehicles-top-2024-greenercars-rankings-prices-drop

Acknowledgements

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Author Contributions

LMC performed the calculations, drafted the figures, and wrote the manuscript draft. Both authors contributed equally to the concepts and content of the manuscript, and to its many revisions.

Competing Interests

The authors declare no competing interests.

Supplemental Material

SM1. Projecting Copper Supply

To place the extra copper demand from electrification and fossil fuel replacement in the context of copper availability, we need to project/predict future mined copper output and the total copper supply including recycled copper. The framework we use to do this is that developed by M. King Hubbert (1956) to predict that U.S. oil production. The input to this method is minimal, objective and available: historical production P and its time integration (e.g., the cumulative production Q of the resource). The method assumes that the resource is finite, and technology does not change over the projection period. In our case, this means that the types of copper deposits and the technologies required to explore for and mine them do not change significantly over the prediction period. Since the Hubbert projection is based on past data, it is a business-as-usual projection of copper mining.

The main and valid criticism of Hubbert's method is that new technologies or new deposit types will change the projection (e.g., see Deming, 2023). This is true. Hubbert's method applies only to a resource accessed by the same technologies and defined by the same types of deposits. When shale gas and shale oil (a new type of resource) production came online, the decline from the peak production Hubbert predicted was abruptly reversed. Production will depart from our copper production guideline when humanity starts to significantly mine the oceans, and will likely depart as humanity explores for, and mine, copper deposits from depths substantially deeper than the present ~500 m. This, however, does not vitiate the utility of the copper production, business-as-usual, baseline we define. If anything, it increases its utility, since departures from its projected copper production (either up or down) will indicate the need for a clear explanation. It is in this context of developing a copper production business-as-usual baseline that we apply Hubbert's method. His method was summarized clearly and comprehensibly by Deffeyes (2005). We use the methods Deffeyes articulated and are indebted to his excellent elucidations.

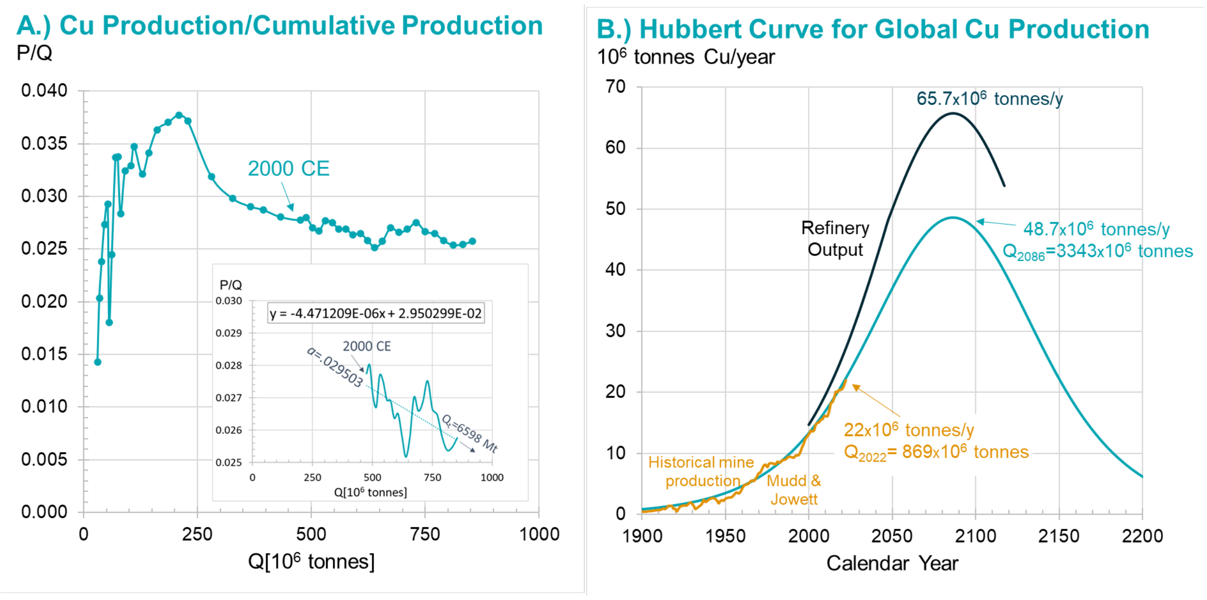

Figure SM1.1. (A) plot of copper production P divided by cumulative production Q vs cumulative production Q. P is measured in 10^6 tonnes of Cu mined per year, and Q is measured in 10^6 tonnes of copper cumulatively produced over time, assuming an amount of mined copper in 1900 AD. The insert plots this data from 2000 to 2022 CE and shows the best-fit linear trend line. The data *for this insert is from the USGS National Minerals Information Center (https://www.usgs.gov/centers/national-minerals-information-center/copper-statistics-and-information). The data prior to 2000 CE (A) is from digitization of the copper production history in Northey et al. (2014). The orange curve in (B) prior to 2000 CE is digitized from Mudd and Jowitt (2018). The plots and the data from which they are constructed are provided in SM4_Tab 1.*

Figure SM1.1 applies Hubbert's method to copper. Figure SM1.1A shows that the variability in the ratio of production to cumulative production decreases and that the ratio of production to cumulative production P/Q becomes a reasonably linear trend after about 2000 AD. The insert shows that this trend has y-intercept a= 0.029503 and an x-intercept Q_t = 6598 Mt (million tonnes) copper. The x-intercept is the total ultimate producible mass of copper. Peak production occurs at 48.7 Mtpy in 2086. The production rate is a function of the remaining resource and the cumulative production:

$$P = a\left(1 - \frac{Q}{Q_t}\right)Q \quad . \qquad \text{(SM1.1)}$$

Equation (SM1.1) simply adds a cutoff to initial exponential growth. When cumulative production is much less than the ultimate total, e.g. $Q \ll Q_t$, the production rate is proportional to the cumulative production and grows exponentially with an interest rate a. This exponential growth is terminated when the remaining resource fraction $\left(1 - \frac{Q}{Q_t}\right)$ becomes small and goes to zero as Q approaches Q_t. When the resource is exhausted (all mined out), production of that resource stops.

Equation (SM1.1) defines the teal Gaussian-shaped curve in Figure SM1.1B. The method is as follows: Some assumed cumulative production in 1900, Q_{1900}, is substituted into (SM1.1) and the production P that year is calculated. This production is added to Q_{1900} to obtain Q_{1901}, and the production in 1901 is calculated. Continuing this process results in an initial version of the blue curve in Figure SM1.1B. For a particular selection of Q_{1900} the production at 2018 will equal the known production rate of 20.4 Mtpy. This Q_{1900} however will produce a different plot in Figure SM1.1A and slightly different values of a and Q_t. Using these values with (SM1.1) will mean a different value of Q_{1900} is needed for P_{2018}=20.4 Mtpy, and this new value of P_{2018} will modify a and Q_t. A few iterations suffices to find a fully compatible set of a, Q_t, and Q_{1900}. This set defines the blue curve in Figure SM1.1B which tracks the historical production very closely and indicates a total copper resource Q_t = 6598 Mt.

From the history of copper production and the cumulative production at one particular time, the Hubbert method determines the full history of production history including the peak production, the date at which it will occur, and the total amount of the resource that will ultimately be produced (the area under the production curve). This is quite remarkable. Furthermore, the production prediction is made from only the last part of the past production history, in our case the production history since 2000 CE. Production over this period is well defined. The calculations discussed above are carried out in SM4 tab 1. There, two historical production curves are used to predict future copper production: One from Northey et al. (2014) and one from Mudd and Jowett (2018). The results are shown in Figure SM1.2. The global copper production curves are identical over the period of interest (2018-2050); the peak production rates, the peak times, and the total copper resource are slightly different, indicating a weak dependence of the production projection on the pre-2000 CE history of production. The production histories after 2000 CE are identical in the cases shown.

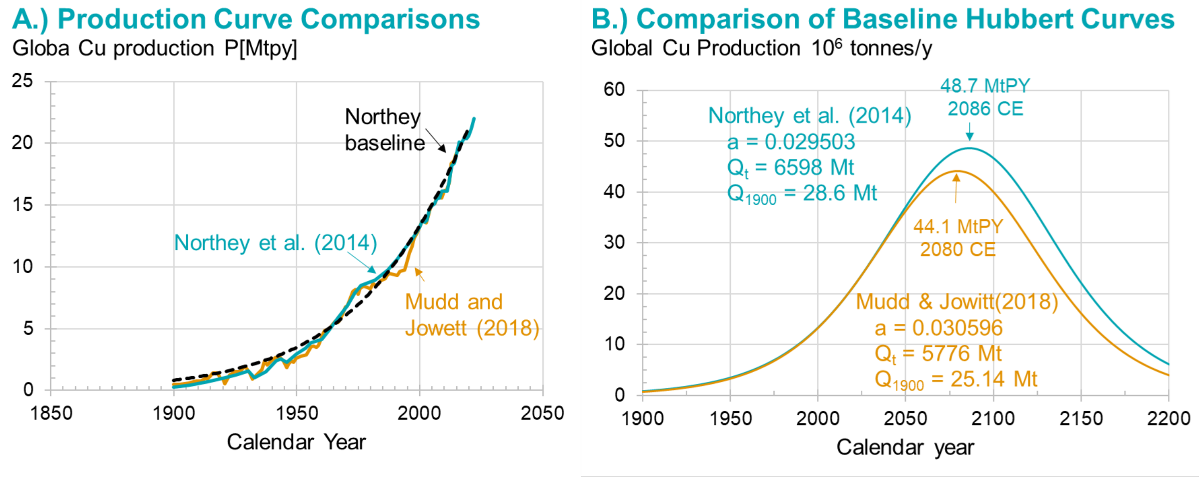

Figure SM1.2. *(A) Production histories from Northey et al. (2014), Mudd and Jowitt (2018), and the Hubbert curve (Northey baseline) determined from the Northey production history. (B) Comparison of the mining-as-usual baseline Hubbert curves determined from the Northey et al. (2014) and Mudd and Jowitt (2018) production histories. Both take the production since 2000 from the USGS Minerals Information Center. Plots are created SM4_Tab 1.*

The mined copper production does not equal the copper supply. The copper produced by refineries is greater than the mined copper in any given year because scrap copper and inventories from other years are also inputs to the refineries. As shown in Figure SM1.3, the fraction by which global refined copper supply exceeds mined copper production has been increasing steadily at about 0.516% per year since 2000 AD. We call this fractional refinery excess the recycle fraction f_{rcyl}:

$$f_{rcyl} = \frac{R_{Cu} - P}{P} \quad . \tag{SM1.2}$$

Here R_{Cu} is the refinery copper output in 10^6 tonnes per year, and P is the amount of copper mined each year as discussed above.

The refinery copper output is plotted as the black line in text Figure 1A labeled “Refinery Output”. This line is computed from the teal mine copper output in that figure assuming that in 2018 f_{rcyl}=0.196, R_{Cu}=24.4 Mt, and P=20.4 Mtpy. As illustrated in Figure SM1.3, we assume f_{rcyl} changes by 0.516% each year before and after 2018, but is capped at 0.35. f_{rcyl} reaches 0.35 in 2048.

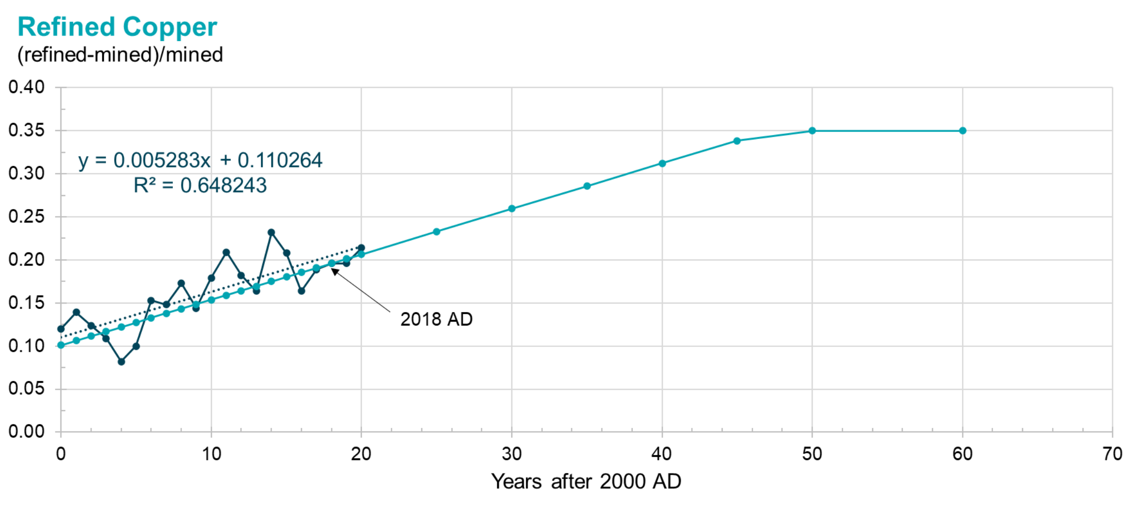

Figure SM1.3. Plot of the fraction by which global refinery output exceeds mined copper production each year. Linear regression shows the fraction changes by 0.516% per year. For use in text Figure 1 the fraction is registered to its value in 2018, and extrapolated as indicated by the teal line. The fraction is calculated from data of the USGS National Minerals Information Center (https://www.usgs.gov/centers/national-minerals-information-center/copper-statistics-and-information). Plot is created in SM4_Tab 2.

A refinery excess over copper mine output is not the same as the recycling rate. The latter is properly defined as the percentage of copper that is reclaimed for other uses when the useful life of some product has ended. There are many products with different usage lifetimes and different fractions of copper recoverable, and recovery fractions can change with time. Obtaining an ensemble average is challenging. Harmsen et al. (2013) gives an example of 2% production growth that suggests recycling rates of 43% and 70% corresponds to f_{rcyl} of 0.23 and 0.35 respectively. A recycling rate of 70% is thought to be near the feasible upper limit of recycling because much copper usage is currently in very small parts of complex electronics and cannot be recycled.

SM2. Baseline Copper Demand

Yergin et al.'s (2022) projection of non-energy-transition copper *demand* is another baseline projection which can be compared to the baseline projection of refinery output (copper supply). This baseline is the sum of copper demands not related to the energy transition, demand from the business-as-usual part of electric grid expansion and maintenance, and demand from the manufacture of internal combustion (ICE) vehicles. Figure SM2.1 shows Yergin et al.'s projection of non-energy-transition copper demand (bottom dark blue bars). Figure SM2.2 shows Yergin et al.'s projection of copper demand for grid development (bottom light green bars), and Figure SM2.3 shows how we separate out the business-as-usual from the bump in grid demand needed for the grid to accommodate EV. Figure SM2.4 shows that this business-as-usual demand baseline is nearly identical to the refinery baseline. Table SM2.1 gives numerical values for the curves in Figure SM2.4.

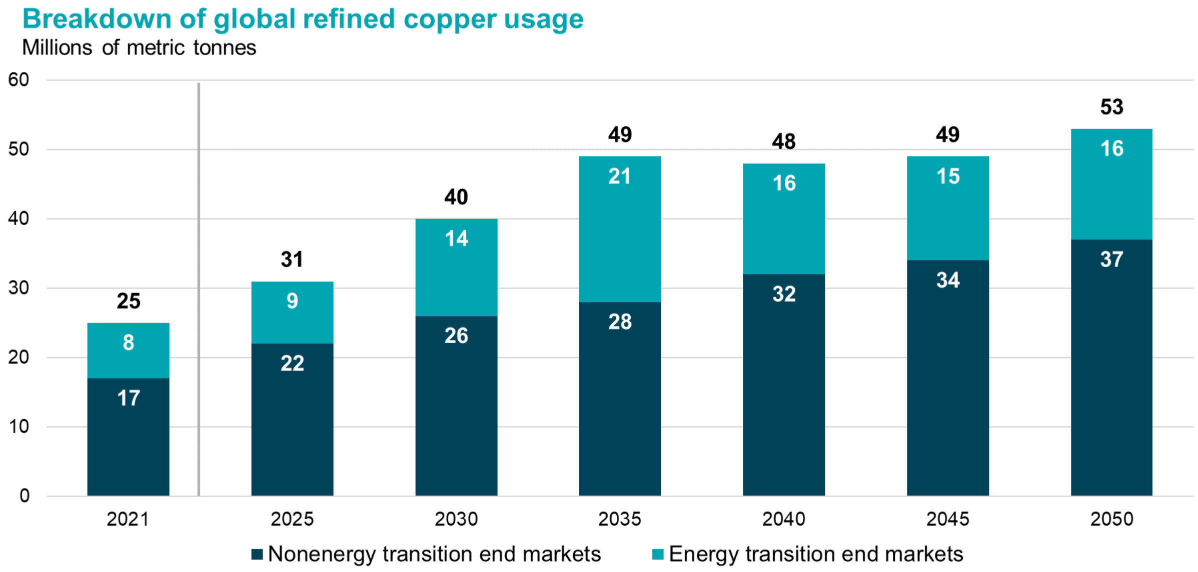

Figure SM2.1. *Yergin et al.'s (2022, p44) projection of non-energy-transition copper demand (dark blue bars).*

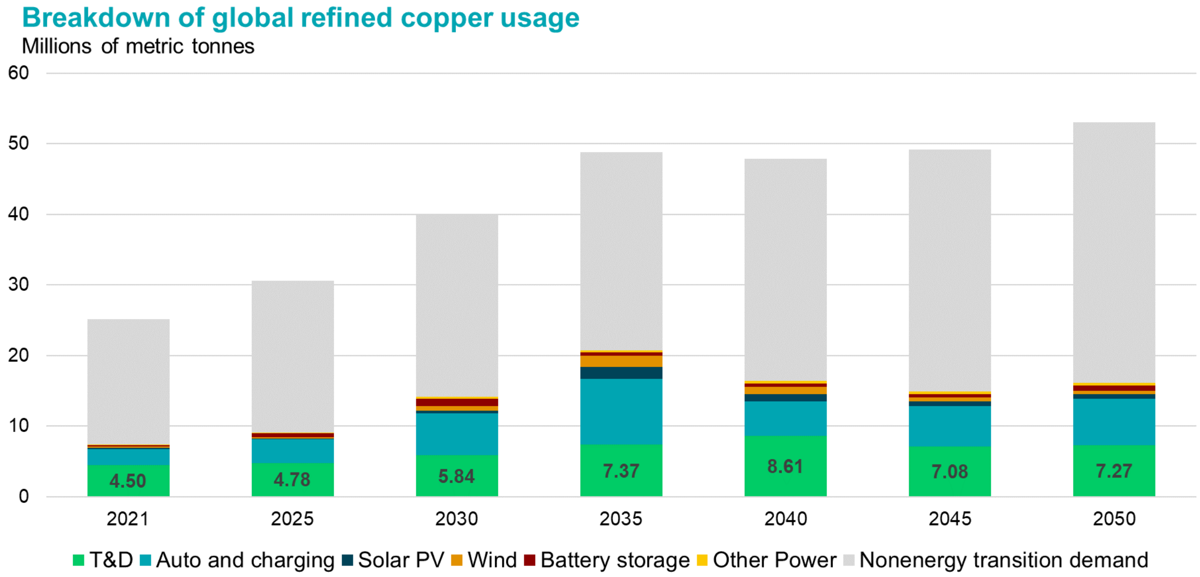

Figure SM2.2. *Yergin et al.'s (2022, p38) projection of transmission and delivery copper demand from 2021 to 2050 (bottom green bars).*

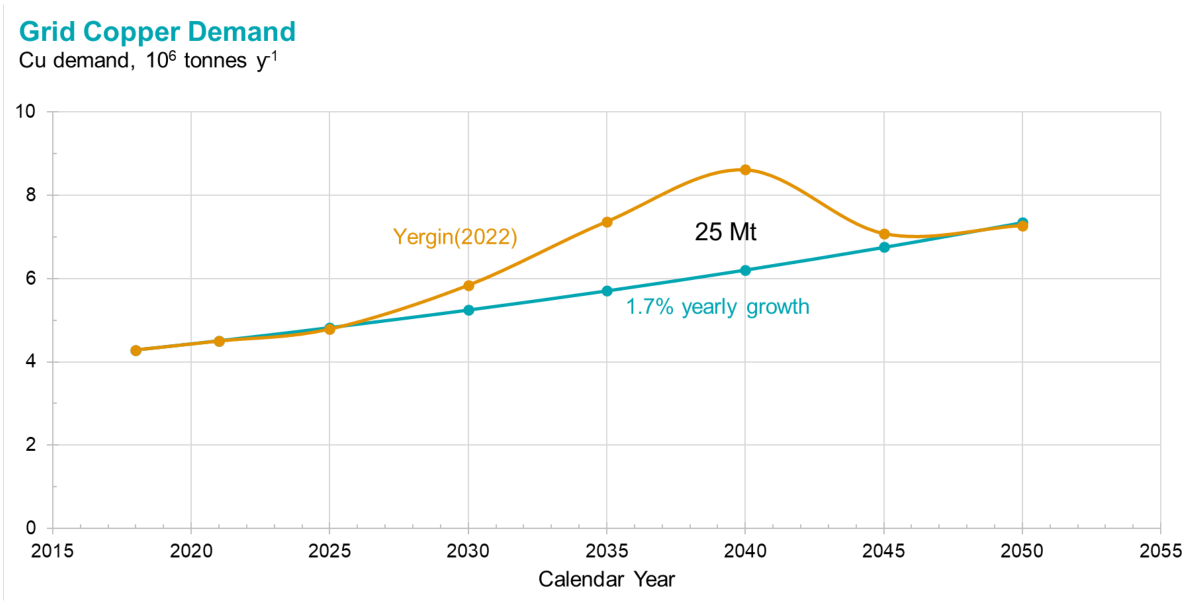

Figure SM2.3. *Yergin et al.'s projection of grid-related copper demand from Figure SM2.2 (orange curve) and its 1.7% business-as-usual growth component (teal curve). The extra copper needed for EV and the green energy transition is 25 Mt copper, similar to the 27 Mt estimated by Chen et al.(2023)in their least-ambitious STEPS fossil fuel replacement scenario. Plot is created in SM4_Tab 3.*

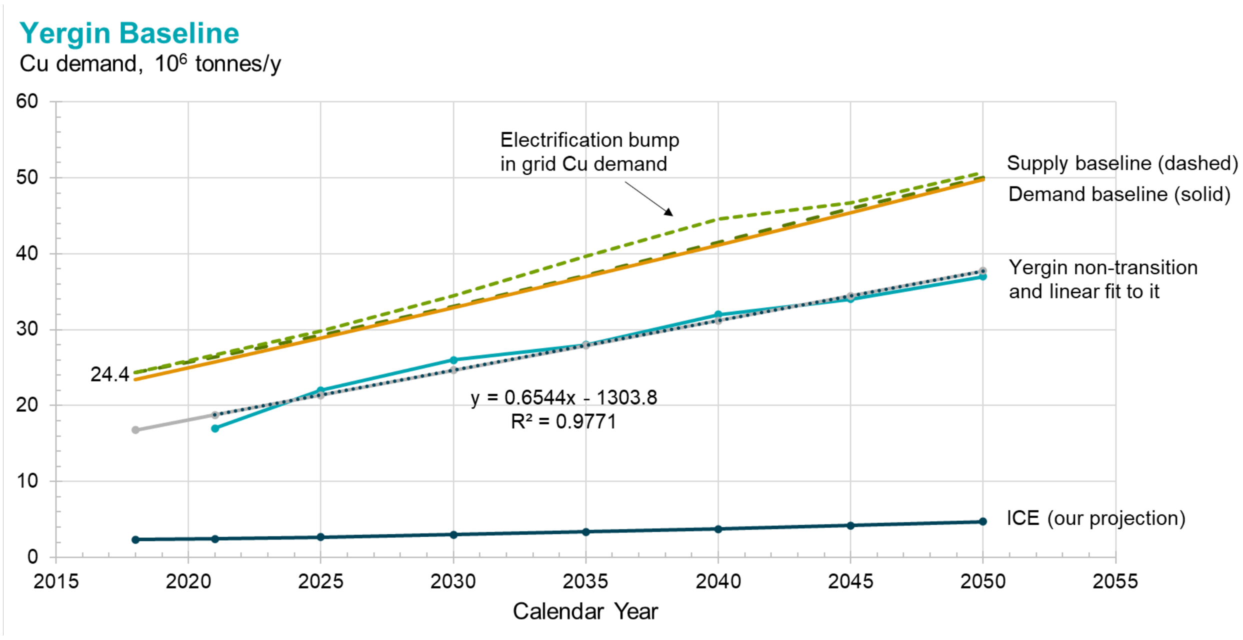

Figure SM2.4. *Comparison of business-as-usual demand baseline of Yergin et al. (2022) (upper solid orange curve) and our refinery output (copper supply) baseline (dark green dashed curve). Data are listed in Table SM2.1. Plot is created in SM4_Tab 3.*

Table SM2.2*. Columns A, B, C and E are data from Yergin et al. (2022) and our calculations as discussed in the text of this SM. Columns D and F are additions of this data that are plotted in Figure SM2.4.*

	A *Linear fit to non-transition demand*	*B* *Projected ICE demand Table SM3.4*	*C* *1.7% grid growth demand*	*D* *electrification bump in grid demand*	*E* *Refinery output (supply baseline)*	*F* *B as U demand baseline A+B+C*
2018	16.78	2.33	4.28	0	24.38	23.39
2021	18.74	2.45	4.50	0	26.39	25.70
2025	21.36	2.69	4.82	0	29.24	28.87
2030	24.63	3.00	5.24	0.59	33.06	32.85
2035	27.90	3.35	5.70	1.67	37.16	36.96
2040	31.18	3.75	6.20	2.41	41.49	41.13
2045	34.45	4.20	6.75	0.33	45.99	45.40
2050	37.72	4.72	7.34	0	50.05	49.78

The non-energy-transition demand (teal curve in Figure SM2.4) increases nearly linearly with time. A linear version of it is plotted as the grey curve. Our projection of copper demand for ICE manufacture (Table SM3.4 in the next SM section) also increases almost linearly (dark blue curve). Adding the linearized version of the non-transition demand, our ICE demand, the 1.7% per year grid growth demand (teal curve in Figure SM2.3) results in the top orange curve in Figure SM2.4. It is nearly coincident to our baseline refinery output (black dashed line) from the previous section. This shows that the refinery baseline can be consideration a projection of either supply or demand. Of course, copper supply should equal demand in any valid prediction. The demonstration that this is so is a new contribution of this paper. The top dashed light green curve in Figure SM2.4 adds Yergin’s electrification bump in grid demand to the refinery (supply) curve.

SM3. Data and Methods

SM3.1 Copper demand from conversion of ICE to EV or Hybrid

Following Michaux (2021), five weight classes of vehicle and four regions (the United States (U.S.), the European Union (EU), China, and the rest of the world (RoW) are considered. The copper needed to manufacture three types of vehicle (EV, hybrid, and ICE) is calculated from the copper needed to manufacture each weight class of vehicle. The number of vehicles manufactured in each region is extrapolated according to recent trends. It is assumed that in the future the percentage of vehicles manufactured in each weight class in each region is the same as in 2018.

Table SM3.1. *N_{ij}: Millions of vehicles in 2018 in five weight classes i and four regions j.*

Class,i	*U.S.$^{1/}$*	*EU$^{2/}$*	*China$^{3/}$*	*RoW$^{4/}$*
Class 8 truck	4.7	5.7	7.1	11.4
Bus	7.9	0.7	1.2	19.2
Light Truck/Van	161.8	27.4	18.4	393.7
Passenger Car	79.0	222.7	203.7	190.5
Motorcycle	16.2	4.5	1.9	39.5
Sum (except motorcycle)	253.4	256.5	230.4	614.8

Michaux, 2021, 1/ T12.2 p271, 2/T12.5 p277, 3 and 4/T12.8 p 283. T indicates Table and p page. Data is from: U.S. Department of Transportation, Bureau of Transportation Statistics: National Transportation Statistics

Table SM3.2. *C_{ik}: tonnes of copper content in in each weight class i for vehicle type k. From Yergin et al. (2022, p 29). Motorcycles are assumed to need 1/3 the copper of passenger cars.*

Class, i	*Cu_{EV}*	*Cu_{Hyb}*	*Cu_{ICE}*
Class 8 truck	0.425	0.035	0.024
Bus	0.139	0.031	0.024
Light Truck/Van	0.060	0.029	0.024
Passenger Car	0.060	0.029	0.024
Motor cycle	0.020	0.010	0.008

Table SM3.3. *V_{jd}: Millions of vehicles (excluding motor cycles) manufactured in each region j at dates d. Data is from dashed extrapolations in Figure SM3.1 below.*

region, j	*2018*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
U.S.	10.9	10.9	10.9	10.9	10.9	10.9	10.9
EU	11.0	11.0	11.0	11.0	11.0	11.0	11.0
China	25.7	31.6	36.7	42.5	49.3	57.1	66.2
RoW	48.1	57.1	64.7	73.2	82.8	93.6	105.9

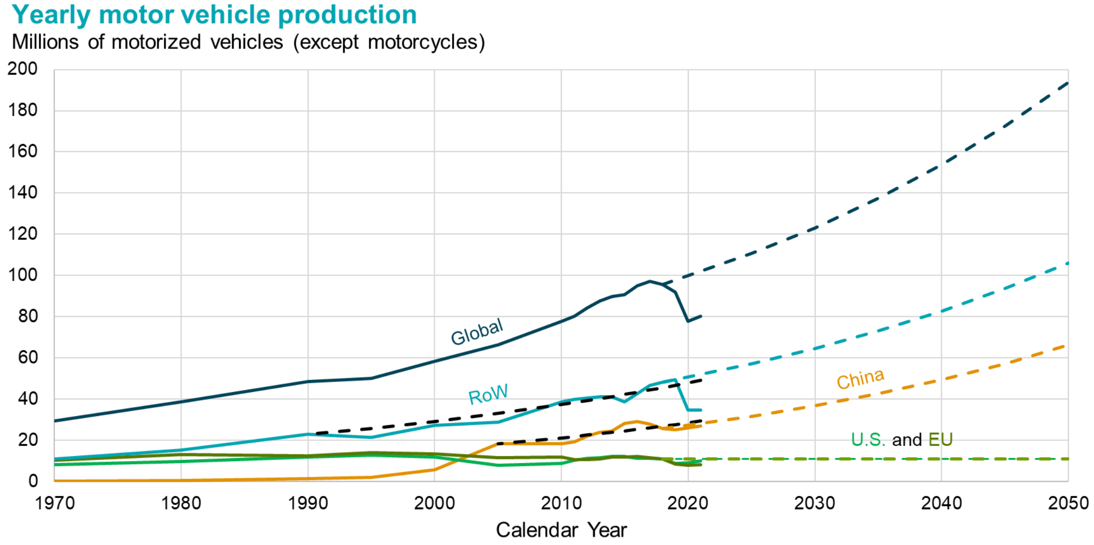

Figure SM3.1. *The total number of motorized vehicles (except motorcycles) manufactured yearly from 1970 to 2021 for the regions discussed is shown by solid curves. Black dashed lines on the middle two curves indicate how growth rates are estimated from this historic data. Colored dashed curves show how the manufacturing rates are projected to future dates, d, for the regions, j, starting from the manufacturing in 2018. The global historical and projected production (uppermost dark blue curves) is the sum of the regional productions. Regional production data is from https://en.wikipedia.org/wiki/List_of_countries_by_motor_vehicle_production. Plot and data are in SM4 tab 4.*

The copper M_{kd} needed to manufacture EV, Hybrid, of ICE vehicles at dates d is calculated:

$$M_{kd} = \left(N_{ij}^{T} C_{ik}\right)^{T} r_{jd} \quad , \qquad \text{SM3(1)}$$

where T indicates the matrix transpose, adjacent subscript indices are summed, and subscript *i* is the weight class of the vehicle, *j* is the region, *k* is the vehicle type, and *d* is the date of manufacture. The ratio r_{jd} is the millions of vehicles manufactured at the dates in Table SM3.3 divided by the millions of vehicles in the 2018 fleet from the last line in Table SM3.1. In other words, $r_{jd}=V_{jd}/N_j^{2018}$, where N_j^{2018} is the last line in Table SM3.1. M_{kd} is listed in Tables SM3.4. Tables SM3.5 and SM3.6 are straight-forward manipulations of Table SM3.4. SM4 tab 6 lists and illustrates an APL script for calculating these tables.

Table SM3.4. *M_{kd}, Millions tonnes of copper needed for manufacture of vehicle type k at dates d calculated using equation SM3(1).*

Vehicle type, k	*2018*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
EV	6.76	7.82	8.71	9.73	10.90	12.23	13.75
Hybrid	2.83	3.28	3.65	4.07	4.56	5.11	5.74
ICE	2.33	2.69	3.00	3.35	3.75	4.20	4.72

Table SM3.5. *Millions tonnes of extra copper relative to ICE.*

Vehicle type, k	*2018*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
EV-ICE	4.43	5.13	5.72	6.39	7.15	8.03	9.03
Hybrid-ICE	0.50	0.58	0.65	0.72	0.81	0.91	1.02
ICE-ICE	0	0	0	0	0	0	0

Table SM3.6. *Millions tonnes of extra copper if conversion of ICE to EV or Hybrid is phased in linearly between 2018 and 2035.*

Vehicle type, k	*2018*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
EV-ICE	0	2.11	4.03	6.39	7.15	8.03	9.03
Hybrid-ICE	0	0.24	0.46	0.72	0.81	0.91	1.02
ICE-ICE	0	0	0	0	0	0	0

Conversion of cars and light trucks/vans constitutes 90% to 95% of the extra copper demand. Most of the conversion vehicle manufacture copper demand is from China and the RoW. In 2018 these regions constitute over 77% of the vehicle copper demand, and in 2050 they will constitute over 90%. The copper demand for manufacturing ICE vehicles, and even more so EV or Hybrid vehicles, resides in the developing world.

SM3.2 Current mining rates

Table SM3.7 lists the yearly copper output of the top 10 currently producing mines. Their total output is 4.72x10^6 tonnes per year. The average mine in this list produces 0.472x10^6 tonnes of copper per year.

Table SM3.7. *Copper production from world's top 10 producing mines in 10^6 tonnes Cu per year. Data are from https://www.mining-technology.com/marketdata/ten-largest-coppers-mines/ .*

	2022
Escondida, Chile	1.060
Collahuasi, Chile	0.589
El Teniente, Chile	0.456
Cerro Verde, Peru	0.434
Morenci, Arizona	0.401
Grasberg Block Cave, Indonesia	0.396
Chuquicamata, Chile	0.373
Cobre Panama, Panama	0.345
Kamoa-Kakula, Congo	0.334
Buenavista del Cobre, Mexico	0.332
TOTAL	**4.719**

SM4. Excel spreadsheet

The excel spreadsheet, provided at https://www.ief.org/_resources/files/reports/sm4-copper-report_vf.xlsb, contains all the calculations upon which this paper is based. The spreadsheet plots all the figures in the paper and supplemental materials. The spreadsheet constitutes a complete documentation of everything discussed in the text.

Tab 1 Constructs the baseline mining curve for copper and plots Figures 1A and SM1.1.

Tab 2 Captures the difference between refinery and mine output and plots Figure SM1.3.

Tab 3 Computes Yergin's demand baseline and plots Figures SM2.3 and SM2.4.

Tab 4 Projects vehicle production and plots Figure SM1.4.

Tab 5 Calculates the extra copper required to phase in EV (or Hybrid) manufacture between 2018 and 2035. Plots Figure 1B.

Tab 6 Lists and illustrates APL script that calculates Tables SM3.4, SM3.5, and SM3.6.

References

Chen, Zhenyang, Rene Kleijn, and Hai Xiang Lin. 2023. “Metal Requirements for Building Electrical Grid Systems of Global Wind Power and Utility-Scale Solar Photovoltaic until 2050.” *Environmental Science & Technology* 57 (2): 1080–91. https://doi.org/10.1021/acs.est.2c06496.

Deffeyes, Kenneth S. 2006. "Beyond Oil: The View From Hubbert's Peak". New York, Hill and Wang, 202p.

Deming, David. 2023. “M. King Hubbert and the Rise and Fall of Peak Oil Theory.” *AAPG Bulletin* 107 (6): 851–61. https://doi.org/10.1306/03202322131.

Harmsen, J.H.M., A.L. Roes, and M.K. Patel. 2013. “The Impact of Copper Scarcity on the Efficiency of 2050 Global Renewable Energy Scenarios.” *Energy* 50 (February): 62–73. https://doi.org/10.1016/j.energy.2012.12.006.

Hubbert, M.K. 1956. "Nuclear energy and the fossil fuels: Shell Development Company." Publication No. 95, 40p.; published on 8 Mar 2006 by Energy Bulletin. http://home.hiroshima-u.ac.jp/er/ZR11_Z_03.html. (1956)

Michaux, S.P. 2021. "The Mining of Minerals and the Limits to Growth". Geological Survey of Finland: Espoo, Finland.

Mudd, Gavin M., and Simon M. Jowitt. 2018. “Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply.” *Economic Geology* 113 (6): 1235–67. https://doi.org/10.5382/econgeo.2018.4590.

Northey, S., S. Mohr, G.M. Mudd, Z. Weng, and D. Giurco. 2014. “Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining.” *Resources, Conservation and Recycling* 83 (February): 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005.

Yergin, D., Hoffman, F., Mothersole, J., Rajan, K., Bonakdarpour, M. 2022. "The Future of Copper: Will the looming supply gap short-circuit the energy transition?." S&P Global Market Intelligence.

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