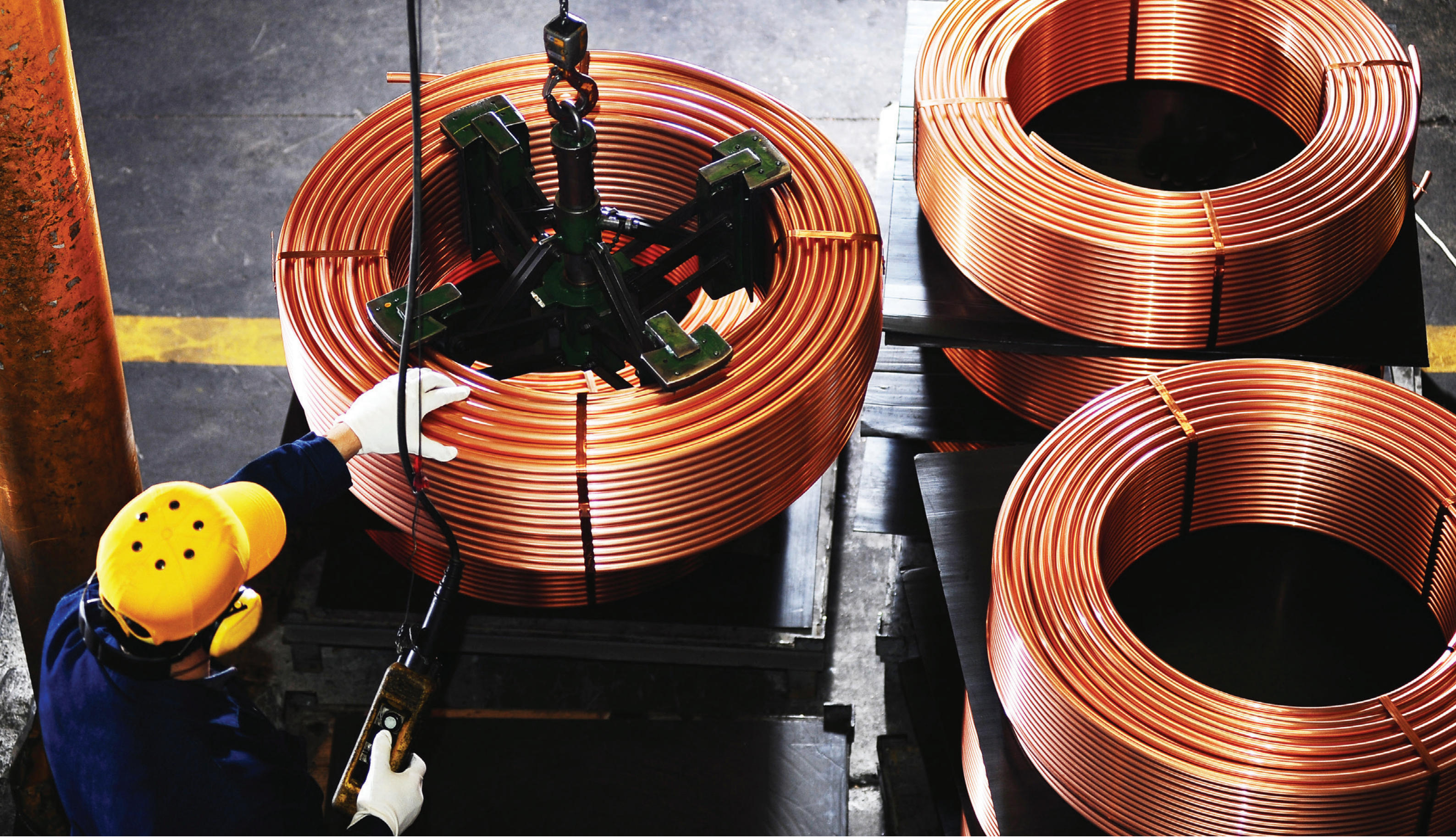

The Future of Copper

Will the looming supply gap short-circuit the energy transition?

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Study objective

A number of authorities have expressed alarm as to whether there will be enough minerals to meet the requirements for the goal of Net-Zero Emissions by 2050. These include, among others, the US government, the European Union, the International Monetary Fund (IMF), the World Bank, and the International Energy Agency (IEA). The last, the IEA, has summarized the challenge as being driven by the move from “a fuel-intensive to a mineral-intensive energy system.”

This study seeks to respond to that concern by focusing on copper, which can be described as the “metal of electrification.” Many nations, including the United States and the European Union, have set Net-Zero Emissions by 2050 as their climate goal. Accordingly, this target was chosen as the basis for the study.

The study seeks to quantify the amount of additional copper that will be required by increased electrification and the energy transition—most specifically, the rapid move to electric vehicles (EVs) and renewable electricity and the need for increased electricity infrastructure. It concludes that copper demand will double by 2035 and continue to grow thereafter. On the supply side, it finds how challenging that will be, whether on the basis of current trends or with an unprecedented acceleration of supply from mining and recycling.

The study makes no policy recommendations. Rather, it seeks to respond to the urgent concern of the authorities above and others by quantifying the copper requirements of Net-Zero Emissions by 2050 and benchmarking them against the supply response. We hope that this study will be a contribution to the continuing dialog about achieving Net-Zero Emissions by 2050.

S&P Global is exclusively responsible for this report and all of the analysis and content contained herein. It represents the collaboration of S&P Global’s Commodity Insights, Economics and Country Risk unit within Market Intelligence, and Mobility divisions. The analysis and metrics developed during the course of this research represent the independent analysis and views of S&P Global and are intended to contribute to the dialogue on the copper required to meet the energy transition requirements under Net-Zero Emissions by 2050.

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Contents

Key findings

- Copper—the "metal of electrification"—is essential to all energy transition plans. But the potential supply-demand gap is expected to be very large as the transition proceeds. Substitution and recycling will not be enough to meet the demands of electric vehicles (EVs), power infrastructure, and renewable generation. Unless massive new supply comes online in a timely way, the goal of Net-Zero Emissions by 2050 will be short-circuited and remain out of reach.

- Copper demand is projected to grow from 25 million metric tons (MMt) today to about 50 MMt by 2035, a record-high level that will be sustained and continue to grow to 53 MMt by 2050. Power and automotive applications will have to be deployed at scale by 2035 in order to meet the 2050 net-zero targets.[1]

- The chronic gap between worldwide copper supply and demand projected to begin in the middle of this decade will have serious consequences across the global economy and will affect the timing of Net-Zero Emissions by 2050.

- The shortfall will reach as high as 9.9 MMt in 2035 in the Rocky Road Scenario, which is based on a continuation of current trends in capacity utilization of mines and recycling of recovered copper. This would mean a 20% shortfall from the supply level required for the Net-Zero Emissions by 2050 target.

- The gap arises even under assumptions of aggressive capacity utilization rates and all-time-high recycling rates in the High Ambition Scenario. Even with these aggressive assumptions, refined copper demand will outpace supply in the forecast period up to 2035.

- In the 21st century, copper scarcity may emerge as a key destabilizing threat to international security. Projected annual shortfalls will place unprecedented strain on supply chains. The challenges this poses are reminiscent of the 20th-century scramble for oil but may be accentuated by an even higher geographic concentration for copper resources and the downstream industry to refine it into products.

- In the United States, the nexus between a politicized regulatory process and the ubiquity of litigation makes it unlikely that efforts to expand copper output in the United States would yield significant increases in domestic supply within the decade. The prospects for any expansions are higher on state and private lands.

- Under the Rocky Road Scenario, the United States will have to import 67%—that is two-thirds—of its refined copper demand by 2035. Even in the High Ambition Scenario, the United States will still need to import 57% of the refined copper during the years of highest energy transition–related copper demand.

- The complexity of permitting mines in the United States is reinforced by the long lead times also required elsewhere around the world. Multidimensional challenges make the development of mines a generational endeavor, spanning decades and requiring hundreds of billions of dollars. Projects under development today would likely not be sufficient to offset the projected shortfalls in copper supply, even if their permitting and construction were accelerated.

1. A metric ton is a metric unit of mass equal to 1,000 kilograms. It is also referred to as a tonne. It is equivalent to approximately 2,204.6 pounds; 1.102 short tons; and 0.984 long tons.

Executive summary

This report examines the looming mismatch, on a global basis, between available copper supply and future copper demand resulting from the energy transition. It highlights the increasing uncertainty surrounding whether burgeoning global climate change ambitions can be satisfied with existing and potential sources. Unless new supply for "the metal of electrification" comes online in a timely way, Net-Zero Emissions by 2050 will be short-circuited and remain out of reach.

Plentiful access to certain "critical minerals" is crucial to delivering on the widespread commitments to eliminate global net carbon dioxide (CO_2) emissions by 2050 (although major emitters like China and India are, respectively, targeting 2060 and 2070).[2] Paramount to achieving these goals is electrifying the global vehicle fleet and aggressively switching to renewable energies for power generation, which are two of the primary prongs of the energy transition.[3] While a variety of metals and rare earth elements have received a great deal of attention by governments, media, think-tanks, and universities, one of the most underappreciated critical minerals is also one of the most familiar and most fundamental—copper. Deeper electrification requires wires, and wires are primarily made from copper. Moreover, copper ore deposits often contain other critical minerals wherein those mining operations yield significant by-product production of other metals such as cobalt, molybdenum, and nickel.

The analysis in this report is built from a detailed bottom-up approach, technology by technology, and compares projected copper demand resulting from the energy transition against projected copper supply. It represents the collaborative work of groups within S&P Global, including the Economics and Country Risk team within Market Intelligence, Commodity Insights, and Mobility.

On the demand side, the analysis works "bottom up"–that is, in a granular way–technology by technology, from assumed implementation of the announced US and EU goals of Net-Zero Emissions by 2050. These policies are the starting point for the analysis, not recommendations. On the supply side, the study offers two views of the future: (1) the High Ambition Scenario, which is based on highly optimistic assumptions about advances in recycling and capacity utilization of mines and refineries; and (2) the Rocky Road Scenario, which is based on a continuation of recent recycling and capacity utilization rates, which are lower.

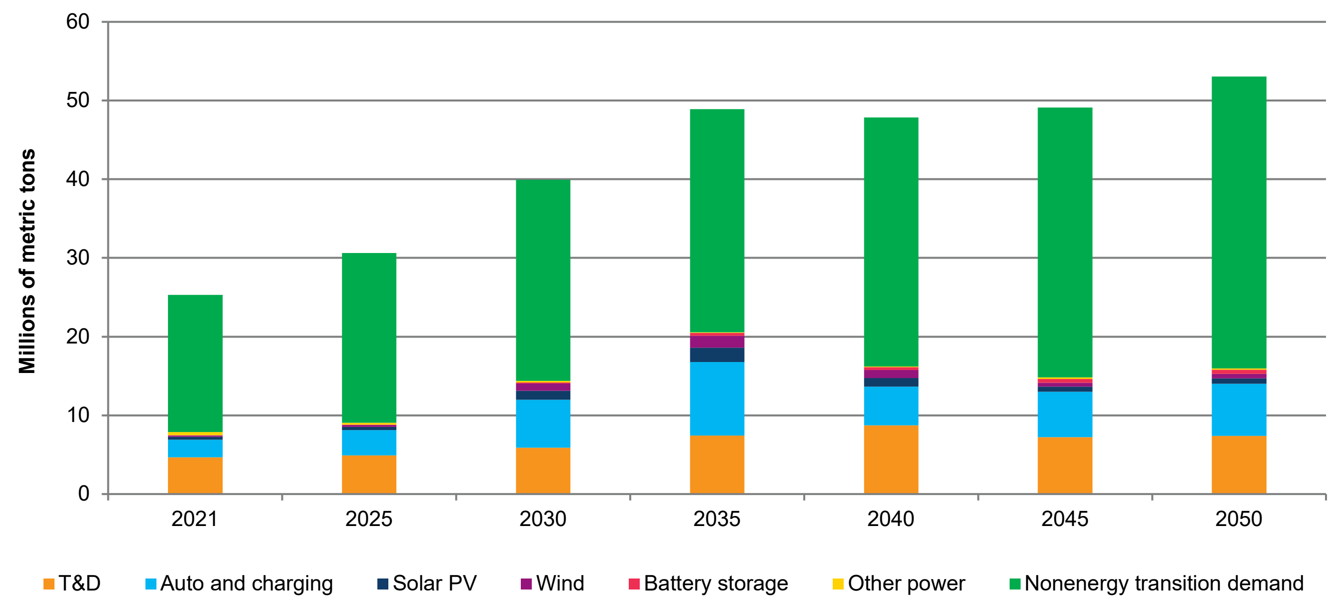
The key point is this: technologies critical to the energy transition such as EVs, charging infrastructure, solar photovoltaics (PV), wind, and batteries all require much more copper than conventional fossil-based counterparts. The rapid, large-scale deployment of these technologies globally, EV fleets particularly, will generate a huge surge in copper demand. Major investments in the power grid to support electrification will further amplify the trend. Meanwhile, copper continues to be a critical material for many other sectors of the economy not directly related to the energy transition but fundamental to overall economic growth and development, and from which copper consumption is projected to grow continuously. The result of the energy transition growth on top of traditional growth will be an overall more than doubling of copper demand by 2050.

2. "Critical minerals" is a term often used in the United States. The list of 50 items (in 2022) produced by the US Geological Survey uses criteria defined in the (US) Energy Act 2020. Most of these are widely used across the industry and may or may not be used in carbon emission–reducing applications. The European Commission similarly produces a "critical raw materials" list; and China published a list of "strategic minerals" under its National Mineral Resources Planning, 2016-2020.

3. Assumptions for electrifying the global fleet includes the increased penetration of fuel-cell electric vehicles, powered by hydrogen.

This study finds that copper demand from the energy transition will accelerate steeply through 2035. Crucially, this dramatic escalation occurs well before 2050 while traditional growth continues to ramp up. The conclusion: achieving the stated climate ambitions will require a rapid and massive ramp-up of copper supply far greater than is visible in any private or public plan.

Global refined copper usage



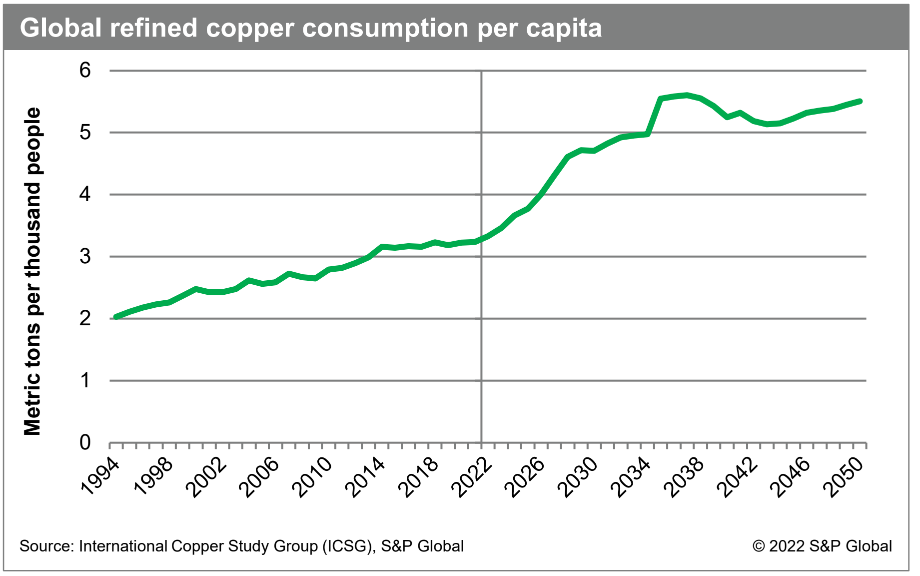
Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. T&D = transmission and distribution; PV = photovoltaics; other power includes conventional generation (coal, gas, oil, and nuclear), geothermal, biomass, waste, concentrated solar power, and tidal.
Source: S&P Global analysis

This energy transition demand growth will be particularly pronounced in the United States, China, and Europe. India will also exhibit strong copper demand growth, albeit more so from traditional copper applications. The High Ambition Scenario assumes that ramped-up demand growth will coincide with record-high rates of copper mine capacity utilization and recycling, but even these aggregated improvements will be insufficient to close the gap. In the Rocky Road Scenario, the shortfall will be much greater, and sooner.

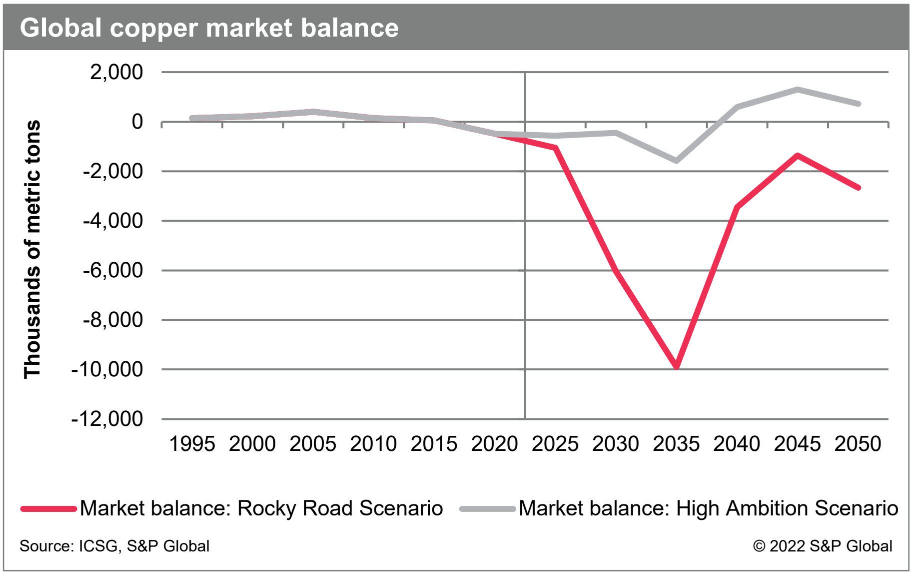
The initial increase in demand over the coming decade will be particularly challenging. Global refined copper demand is projected to almost double from just over 25 MMt in 2021 to nearly 49 MMt in 2035, with energy transition technologies accounting for about half of the growth in demand. The world has never produced anywhere close to this much copper in such a short time frame.

Demand from nonenergy transition end markets—such as building construction, appliances, electrical equipment, and brass hardware and cell phones, as well as expanding applications in communications, data processing, and storage—is also expected to continue to grow, rising at a compounded annual rate of 2.4% between 2020 and 2050. Altogether, total refined copper demand is expected to reach approximately 53 MMt in 2050. It is important to note that copper demand would see significant increases over the projection period even in a world that did not fully transition to net zero. Copper demand from energy transition end markets is expected to reach a maximum of almost 21 MMt in 2035. This surge in demand to meet Net-Zero Emissions by

2050 requires a near doubling of today's global copper supply by 2035, an expansion that current exploration trends or projects in the feasibility stage of development are incapable of meeting.



Per capita consumption of copper has been rising steadily since the early 1990s. Per capita consumption growth will accelerate markedly between 2024 and 2035 as investments to meet Net-Zero Emissions by 2050 targets are made and developing countries continue to industrialize. After the middle of the next decade, copper consumption per capita plateaus as EV sales begin to slow once fleets are mostly electrified. In a world moving to net zero, new copper supplies will be necessary to maintain this elevated level of consumption.



This study finds that copper supply shortfalls begin in 2025 and last through most of the following decade. In the High Ambition Scenario, surpluses will likely emerge in the 2040s as energy transition copper demand slows and secondary production (the refining of recycled copper) sees an upswing. If capacity utilization and recycling rates do not improve and instead reflect their average rates over the past decade—as in the Rocky Road Scenario—then these surpluses would not arise and a much steeper gap between supply and demand would persist through 2050. Unless the considerable gap between demand requirements and supply realities is closed, especially between 2025 and 2035, the 2050 target for net zero will be pushed further into the future.

The challenge will be compounded by increasingly complex global geopolitical, trade, and country-level risk environments. There are several dynamics that will have a particular bearing on copper access. China holds a preeminent position in copper smelting (47%), refining (42%), and usage (54%), in addition to its sizable position in production, making it the epicenter of world copper. Continued trade tensions and other forms of competition between the United States and China could affect the copper market going forward. Supply chain resilience has emerged as a strategic imperative, particularly after the COVID-19 pandemic and the war in Ukraine. The study finds that by 2035 the United States will be importing between 57% and 67%—that is up to two-thirds—of its copper needs. An intensifying competition for critical metals is very likely to have geopolitical implications.

In a period of high demand, prices will rise, which is a stimulus to investment. While price is a significant incentive, there are other considerations that also affect the pace of investment. These include the absence of actual development opportunities, as well as environmental issues, social license to operate, relationships with local communities, and locational accessibility.

The resulting challenge for all actors involved in the energy transition will be to manage sometimes competing and often contradictory priorities. To achieve Net-Zero Emissions by 2050 will likely require major innovations in technology and approaches to policies, including ones that encourage long-term investment, because there is no way to forestall the projected shortages in copper without taking steps to increase supply. Three priority areas stand out for consideration and further refinement given the findings of this study:

- **Policy:** Regulatory and fiscal regimes need to be stable and predictable to encourage investment and facilitate construction of new mines, processing facilities, and recycling plants. Mines are generational endeavors requiring billions, even tens of billions, of dollars with development timelines that span decades. Clear policy objectives that connect critical minerals production with clean energy end-use goals would provide investment stability and assure long-term political acceptance and social license—important steps for reducing the delay in developing new copper resources for the market.

- **Technology:** Innovation that enables cleaner, more efficient, and lower-cost extraction and refining of copper could help increase supply directly. If such innovation addressed environmental and social concerns of a growing portion of investors, then it would also attract more capital into the industry and increase supply indirectly.

- **Interdependencies:** The energy transition will require not only more copper but also other critical minerals, many of which are only produced as co-products or by-products of copper processing (smelting and refining). Some of these are already identified under nascent government initiatives—particularly in the United States and the European Union—while others are not. Understanding these wider interdependencies will be important to ensure that the path forward is not blocked by similar issues emerging for other critical minerals required for increased electrification.

Chapter 1. Introduction

Copper's historical role

Copper is distinctive as a metal in that it is easily stretched, cast, and shaped; resists corrosion; and has excellent alloying properties with other metals. It also conducts heat and electricity extremely well.[4] But that last characteristic was not its historical role.

Copper was one of the first metals ever extracted, with documented human use dating back to around 8,000 BC. For nearly five millennia, copper was the only well-known metal and was used principally in making amulets and other jewelry. It was about 3,000 BC that the discovery that copper could be alloyed with tin to make bronze gave rise to the Bronze Age, with copper then being used widely in tools, weapons, armor, and household items in addition to decorative objects. When alloyed with zinc, the result was brass, which was used in Roman coinage. In the Middle Ages, many uses for brass were found, including for household items, musical instruments, and early mechanical devices. Beginning in the late 18th century and early 19th century, a new application for copper emerged—one with important military impact. Britain's Royal Navy found that copper sheathing could protect the wooden hulls of its ships from rotting away. Paul Revere is famous to Americans for his "midnight ride" at the beginning of the American Revolution, warning the militia outside Boston that British troops were on their way. Less well known is that he later became America's copper pioneer, manufacturing the sheathing for American ships, including for the nascent US Navy.[5]

It was in the 1830s that copper began to find its modern role—its vocation in electricity. Samuel Morse's first models of the telegraph included a few yards of copper wire, with insulation provided by cotton thread. Around the same time, in London, in what was described as a "beautiful series of experiments on the velocity of electricity," Professor Charles Wheatstone demonstrated his concept for the telegraph by sending electricity through a copper wire that stretched almost four miles in length.[6]

For the first time in human history, the telegraph eliminated the need to physically carry a message from a sender to a receiver. In other words, before the telegraph, a message could only be transmitted as fast as it could be physically transported from the source to its destination. The backbone of the near-instantaneous transmittal of messages was the network of copper cables interconnecting the telegraph stations. The use of copper as a conductor was accelerated with the development of the telephone and the electric light bulb, which required a network of wires from a generator to a bulb. All these changes meant a major change in the role of copper: up until roughly a century and a half ago, pure copper accounted for an insignificant portion of its total use as it was mainly used in those alloys. Today, most copper is used in its pure form because of its superior properties as an electrical conductor.

4. Only silver is more conductive—but is many times the price of copper.

5. "I have engaged me," Revere wrote in 1800, "to build me a Mill for Rolling Copper into sheets which for me is a great undertaking, and will require every farthing which I can rake or scrape." Esther Forbes, *Paul Revere and the World He Lived In* (Boston: Houghton Mifflin, 1999), p.424.

6. Russell, Robert W., *History of the Invention of the Electric Telegraph: Abridged from the Works of Lawrence Turnbull, M. D., and Edward Highton, C. E., with Remarks on Royal E. House's American Printing Telegraph, and the Claims of Samuel F. B. Morse, as an Inventor.* United States: W. C. Bryant & Company, printers, 1853, https://www.google.com/books/edition/History_of_the_Invention_of_the_Electric/k6xGAQAAMAAJ?hl=en&gbpv=0, accessed 21 June 2022.

Copper in the energy transition

Since the energy transition means electrification on a vast scale, copper will be critical to that transition's viability. It will be needed to modernize aging power generation and transmission infrastructure to accommodate fast-growing renewable sources—including solar PV, offshore and onshore wind, and concentrated solar power, as well as nuclear and hydropower—and cope with surging demand. Transportation is also electrifying quickly, with rapidly growing sales of EVs in most major markets. Unprecedented quantities of copper will be demanded over the next 25 years. Understanding this unprecedented demand is essential to meeting the challenge ahead. A cascade of reports from international organizations and national governments have raised the alarm about the ability to meet the vast growth in the demand for minerals required by the race to net zero.

- "The shift to a clean energy system," warned the **International Energy Agency (IEA)**, "is set to drive a huge increase in the requirements for these minerals.... A rapid rise in demand for critical minerals – in most cases well above anything seen previously – poses huge questions about the availability and reliability of supply."[7]

- **International Monetary Fund (IMF)**: striving to achieve net zero by 2050 "is likely to spur unprecedented demand for some of the most crucial metals," leading to price spikes that "could derail or delay the energy transition itself."[8]

- **World Bank:** "A low-carbon future will be very mineral intensive because clean energy technologies need more materials than fossil-fuel-based electricity generation technologies.[9]

- **European Commission:** "Access to resources is a strategic security question for Europe's ambition to deliver the Green Deal.... As demand for fossil fuels decreases, increased demand for raw materials, including rare earths and metals, could lead to new supply challenges in the course of the energy transition."[10]

- **US Senate Energy Committee:** "The United States' mineral import dependency and the concentration of mineral supply from certain countries are broadly recognized as growing threats to economic growth, competitiveness, and national security. The resulting price and supply chain volatility has prompted a greater focus on policies related to mineral security and critical minerals that are important in use, susceptible to supply disruption, and for which no substitutes are readily available."[11]

- **Biden administration:** "The United States needs resilient, diverse, and secure supply chains to ensure our economic prosperity and national security.... 'Supply chain,' when used with

7. IEA, "The Role of Critical Minerals in Clean Energy Transitions," IEA, 2021, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary, accessed 21 June 2022.

8. Lukas Boer, Andrea Pescatori, Martin Stuermer, and Nico Valckx, "Soaring Metal Prices May Delay Energy Transition", IMF, 10 November 2021, https://blogs.imf.org/2021/11/10/soaring-metal-prices-may-delay-energy-transition, accessed 21 June 2022.

9. Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, and John Drexhage, "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition," World Bank, 2020, p. 11, https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf, accessed 21 June 2022.

10. European Commission, Directorate-General for Energy, Joint Communication, "EU external energy engagement in a changing world," May 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=JOIN%3A2022%3A23%3AFIN&qid=1653033264976, accessed 21 June 2022.

11. US Senate. Committee on Energy and Natural Resources. American Mineral Security Act (To Accompany S. 1317). (S. Rpt. 116–131). Library of Congress, 2019, https://www.govinfo.gov/content/pkg/CRPT-116srpt131/pdf/CRPT-116srpt131.pdf, accessed 21 June 2022.

reference to minerals, includes the exploration, mining, concentration, separation, alloying, recycling, and reprocessing of minerals."[12]

All these reports focused on the general theme of pressure on minerals and metals. Our report builds up from these reports but is different in two important ways. First, it focuses on only one metal—copper—the most important metal for electrification. And second, it seeks to quantify the copper requirements to achieve Net-Zero Emissions by 2050 in addition to the nonenergy transition copper demand and then benchmarks that against projected global copper supply under two different supply scenarios.

Securing copper supplies

Commitment to the Paris Climate goals imply an intensifying drive—and competition—in the 21st century for the raw materials needed to achieve those goals. The ensuing scramble may be compared to that for fossil fuels in the 20th century. But copper production is more concentrated than oil. The two top producers—Chile and Peru—account for 38% of world production. Prior to Russia's invasion of Ukraine, the three top oil producers—the United States, Saudi Arabia, and Russia—accounted for 40% of world crude oil production. In 2020, China alone accounted for over 40% of the refined copper produced globally. While the United States dominated the copper markets in the first half of the 20th century, China is ahead of the United States in annual copper mine production and ownership of global mining, smelting, and refining assets. Notably, while both the European Union and the United States have highlighted the centrality of minerals in the clean energy transition, neither classifies copper as a critical metal, despite its foundational role. The geopolitical risks and uncertainties about the stability of mineral supplies have been underlined by Russia's invasion of Ukraine in 2022 and the resulting disruption of global mineral and commodity markets.

Methodology

This study examines whether sufficient copper supplies will be available in the time frame required to build and deploy the technologies for achieving the target of Net-Zero Emissions by 2050. It presents a holistic view, drawing on expertise and data across S&P Global's Commodity Insights, Economics and Country Risk unit within Market Intelligence, and Mobility divisions. It is different from other reports and studies in its granularity. That is, the results are quantified using a bottom-up approach. First, we project future copper demand on a technology-by-technology basis, taking into account the prospects for substituting copper with other metals, e.g., aluminum. Second, these demand projections are compared against a dynamic model of future copper supply, which accounts for secondary production (recycling), efficiency gains, and utilization rates. Finally, these quantitative results are placed in their complicated operational context, in which a series of operational issues interact across key sourcing countries to challenge the future of copper supply.

As with any economic model, this analysis is based on certain assumptions that should be clearly identified. This study assumes that the "energy transition," which means different things to different people, is encapsulated by the goal of building the specific hardware intended to

12. The White House, "Executive Order on America's Supply Chains," 24 February 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/, accessed 21 June 2022.

eliminate CO_2 emissions on a net basis by 2050—a goal that has been embraced by the United States and the European Union and numerous other governments around the world. We note, however, that two of the most important emitters—China and India—have set targets that are further out.

This study leverages the S&P Global Multitech Mitigation (MTM) scenario as a credible pathway to model the energy transition. The scenario is built on the assumption that the net-zero emissions goal will be achieved by 2050. This scenario is comparable to the Net Zero by 2050 scenario of the IEA.[13] In S&P Global's other main energy scenarios—Inflections and Green Rules—the Net-Zero Emissions by 2050 target is not achieved as a result of less-aggressive climate policies, economic challenges, political and security considerations, and the inertia of energy systems in transitioning to clean energy sources in a relatively short time frame in a world that currently gets about 80% of its energy from hydrocarbons. Working backward from the implementation, the MTM scenario identifies the pathways needed to make it possible: diversification of energy supply (with solar and wind becoming key energy sources) and rapid electrification of the economy (including rapid conversion of the transportation sector to battery electric and hybrid vehicles). To support this transition, global investments in the electricity grid would need to more than double between today and 2040. This study also assumes that the United States's and European Union's announced strategies will be fully implemented. *Chapter 5: What does this mean for supply?* of this report makes certain assumptions about the copper market that are also clearly identified.This study does not recommend or propose policy actions and outcomes.

13. IEA , "Net Zero by 2050," IEA, Paris, 2021, https://www.iea.org/reports/net-zero-by-2050, accessed 21 June 2022.

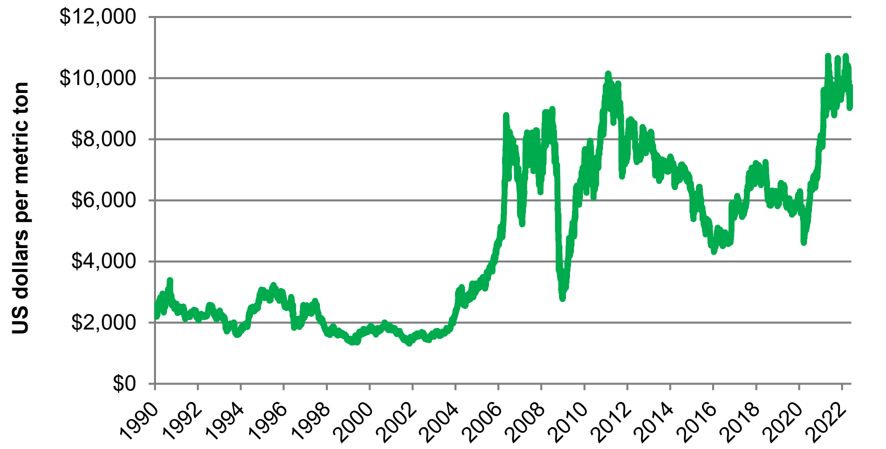
Chapter 2. “Dr. Copper”: A primer

Because of copper’s widespread applications in many cyclically leading sectors of the economy—from homes and manufacturing to electronics, power generation, and transmission—demand for copper has often been a reliable leading indicator of economic health. Indeed, analysts have coined the term “Doctor Copper” to describe its seeming ability to predict turning points in the global economy.

The trends and dynamics of copper demand can be summarized in three distinct time periods:

- First, there was “The Copper Cycle Era” (pre-2002), when copper demand was driven by industrial production in developed countries with copper prices tracking industrial production cycles. This was when Dr. Copper proved his predictive power.
- In the “China Era” (2002–18), growth in global copper demand accelerated owing largely to economic growth and urbanization in China. This was the period that some described as “the commodity supercycle.”

London Metal Exchange copper price



Source: London Metal Exchange, S&P Global © 2022 S&P Global

- The net-zero targets, and government policies and investment behind them, point to a “New Era of Copper Demand,” in which the demands of energy transition will accelerate the growth in copper consumption. The “New Era of Copper Demand” is the subject of this study and may portend another commodity supercycle.

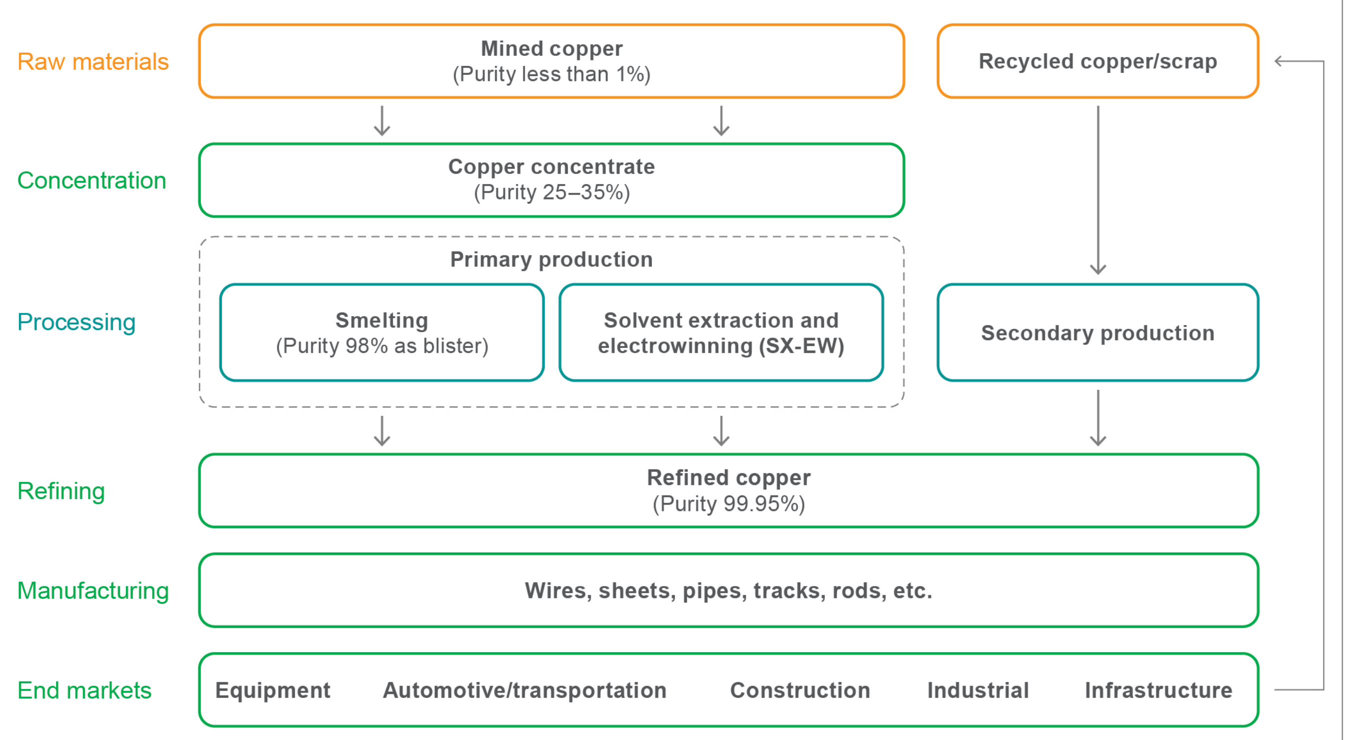
Processing copper

The objective of the entire processing system is to go from mined ore, with less than 1% copper, to a final copper sheet, called a cathode, which is 99.95% pure copper. Whether inside an electrical vehicle or as a plumbing pipe, copper is generally used in its refined state—with a purity of nearly 100%. High-purity copper cathodes that can be worked into the sheets, pipes, wires, and other manufactured products are the end goal of refined production. The production process of copper from mining to refining may take one of multiple routes. Copper ore mined today typically contains only 1% or less copper, in contrast to 150 years ago when ore grades typically exceeded 5% and grades as high as 10% in very rich mines were not unheard of.[14] This deterioration in ore quality necessitates extensive processing. Once copper ore is mined it is

14. On the declining grades in copper ore, Stephen E. Kessler and Adam C. Simon, “Global mineral reserves and resources” chapter 14 in *Mineral Resources, Economics and the Environment*, (Cambridge: Cambridge University Press, 2019).

ground into a concentrate, then smelted and refined, with different processes used to produce high-grade copper (more than 99% copper) depending on the type of ore. Sulfide ore, which is the more common, is generally concentrated through grinding and then further processed through smelting and refining to produce a copper concentrate, which is then heated in a series of furnaces. Then the final high-purity copper "cathode" is made through the refining process, which uses electrowinning for further purification, leaving just the copper behind. In contrast, oxide ore can be leached with sulfuric acid in order to liberate the contained copper in sulfate solution. The solution then undergoes a solvent extraction and electrowinning process (SX-EW) to produce refinery grade copper. Roughly 18% of refined copper today is produced using the SX-EW process. The smelting and production of refined copper from mined copper sources is referred to as "primary production."

Copper: From mining to market



Note: End markets listed are not exhaustive.
Source: International Copper Study Group (ICSG)
© 2022 S&P Global: 2006028

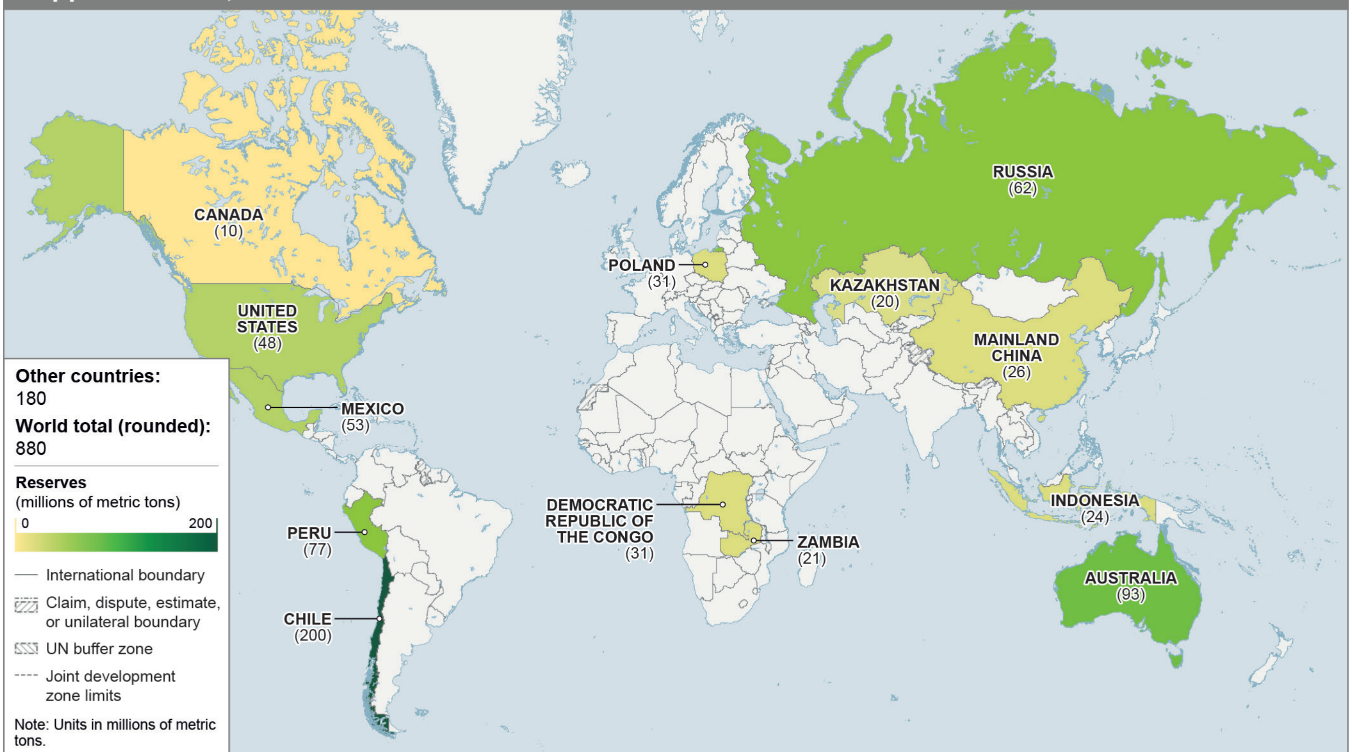
Refined copper can also be produced from scrap or recycled copper. The process of refining copper scrap is similar to the smelting process. High-purity copper scrap is melted in a furnace, reduced, and then formed into either a billet or ingot. Meanwhile, low-purity copper scrap requires smelting to remove unwanted elements before being processed into a billet or ingot. The refining of recycled copper is referred to as "secondary production" or "aboveground mining."

Mapping copper

The total amount of copper on Earth is vast. The US Geological Survey (USGS) estimates that, as of 2015, identified resources contained 2.1 billion metric tons of copper, and undiscovered resources contained an estimated 3.5 billion metric tons.[15] However, only a fraction of this geologic resource is economically viable at present-day prices and using current technologies. As noted above, copper by-products from manufacturing and obsolete products are readily recycled. This so-called "aboveground mine" contributes to supply. However, products made from copper, such as electronic equipment, are recycled with lower frequency than consumable goods made from aluminum, such as food and drink cans, due in part to being more durable than aluminum-based consumable goods. In 2021, secondary (or recycled metal) accounted for 17% of total refined copper supply.[16]

Below are estimates from the USGS on the reserve base, or copper in the ground that has yet to be mined.

Copper reserves, 2021



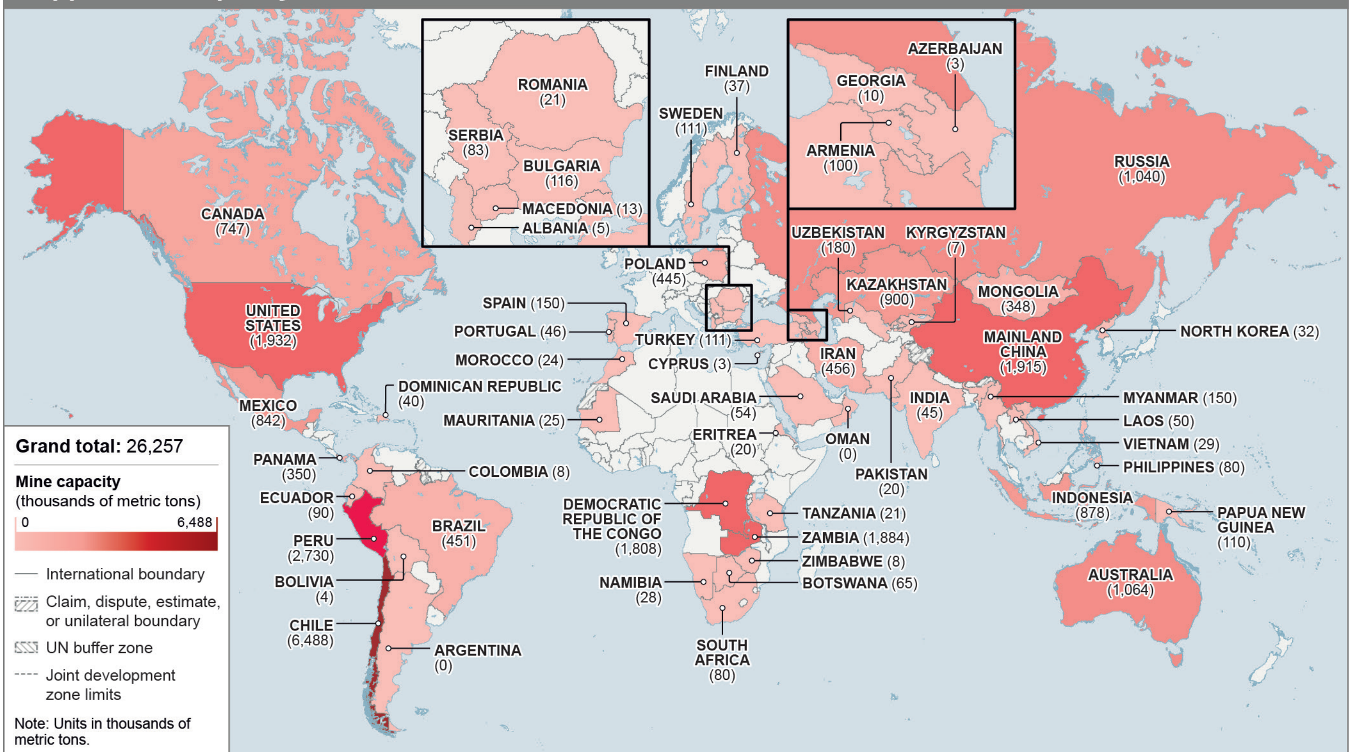
Source: United States Geological Survey/IHS Markit: 2006071

15. Hammarstrom, J.M., Zientek, M.L., Parks, H.L., Dicken, C.L., and the US Geological Survey Global Copper Mineral Resource Assessment Team, "Assessment of undiscovered copper resources of the world, 2015" Version 1.1, 24 May 2019, U.S. Geological Survey Scientific Investigations Report 2018–5160, 619 p., https://doi.org/10.3133/sir20185160, accessed 21 June 2022.

16. International Copper Study Group (ICSG): percentage represents secondary (recycled) production as a percentage of total refined production.

Chile is the largest producer of mined copper and also the country with the largest known reserve base, with 200 MMt of copper estimated to be in the ground. Despite being the sixth-largest producer of mined copper in 2021, Australia is the country with the second-largest known reserve base with 93 MMt. The Democratic Republic of the Congo (DRC), mainland China, and the United States are all larger producers of mined copper than Mexico, yet Mexico has a larger known reserve base than each of these three regions. Generally, however, the reserve base aligns with where copper is currently mined, other than the exceptions noted above.

Copper mine capacity: 2021



Source: International Copper Study Group/IHS Markit: 2006072

As the two largest producers of mined copper, Chile and Peru also are the two countries with the most annual mined copper capacity, a measure defined by the sum of capacity in all copper mines within the country. Despite producing more mined copper than the United States, both mainland China and the DRC have less mined capacity. In the United States, the interaction between the considerable challenges of the permitting process and the ubiquity of continuing litigation is the primary explanation of the country's lower capacity utilization rate compared with mainland China and the DRC. Zambia is the fifth-largest country in terms of mine capacity, but substantial operational risks keep capacity utilization low and prevent the country from entering the top five in terms of mined production.

The processing of copper has a different geography. Copper is not necessarily smelted or refined where it is mined, as is evident in this map. Mainland China accounts for 36% of smelting capacity (and an even higher share for actual smelting), despite making up just 7% of mined copper capacity. Japan and Chile each make up more than 7% of global smelting capacity, and no other country has higher than a 5% share of global capacity. The United States accounts for only 3% of global smelting capacity compared with 7% of total global refined copper usage. This mismatch means that the United States is heavily reliant on imports from other countries to fulfill its copper demand.

Copper smelting capacity: 2021

Source: International Copper Study Group/IHS Markit: 2006073

As is the case for smelting, mainland China is by far the region with the most copper refining capacity, accounting for roughly 35% of global capacity.[17] Chile, the United States, and Japan are the next three countries with the second, third, and fourth most refining capacity, respectively, making up another 21% of global capacity between the three countries.[18]

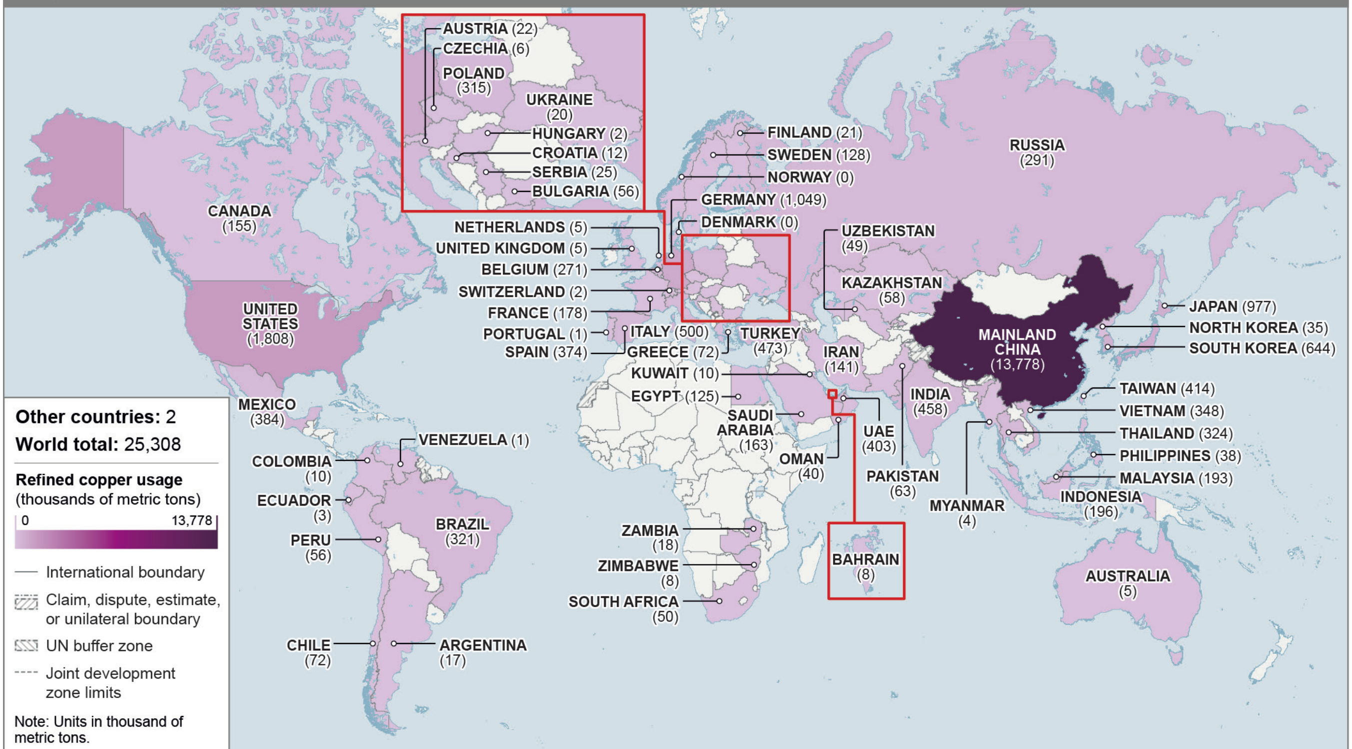
Copper refining capacity: 2021

Source: International Copper Study Group/IHS Markit: 2006074

17. International Copper Study Group Directory of Copper Mines and Plants Up to 2026, published 13 January 2022.
18. Ibid.

Mainland China's footprint in the usage of copper is even larger than its footprint in both the smelting and overall refining of copper. In 2021, it accounted for 54% of global refined consumption.[19] The United States comes in a distant second as the next largest consumer of refined copper, using over 1.8 MMt in 2021. While this is 7% of total global usage, it is only 13% of mainland China's usage. The next three largest users are the industrialized nations of Europe, Japan, and South Korea.

Copper consumption: 2021



Source: International Copper Study Group/IHS Markit: 2006075

19. International Copper Study Group Directory of Copper Mines and Plants Up to 2026, published 13 January 2022.

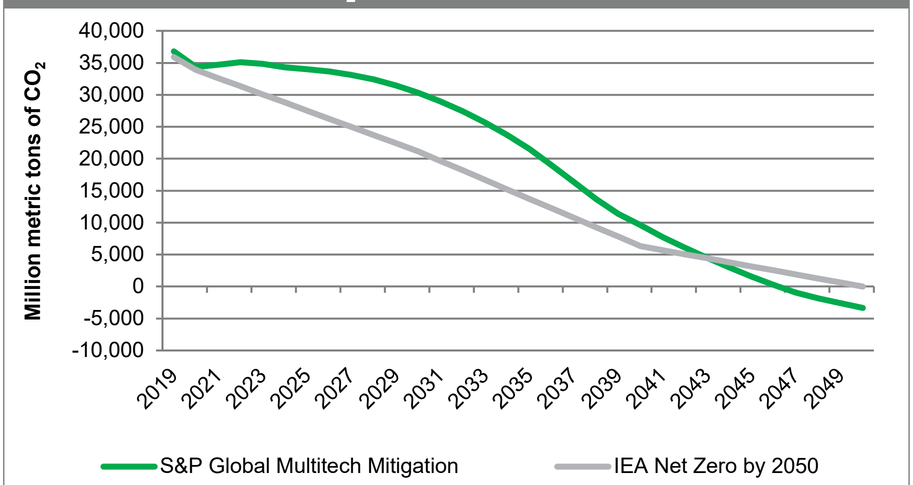
Chapter 3. Copper requirements in the energy transition

Achieving Net-Zero Emissions by 2050 requires massive deployment of low-carbon power and automotive applications many years before that point. These technologies, primarily EVs, and renewables, solar PV, and wind turbines in particular, are more copper-intensive than their traditional counterparts. In addition, investments in the power grid are critical to support this electrification. Overall, these sectors will need an additional 12 MMt per year (MMt/y) of copper by 2035. As a result, these sectors will see double-digit annual growth rates in copper demand over that period.

The race to Net-Zero Emissions by 2050

As described above, this study relies on the S&P Global MTM scenario, which models a credible path for transforming the global economy and energy system to a net-zero emissions reality by 2050. Copper demand is derived from the requirements envisioned under this scenario.

Global scenarios total CO_2 emissions



Source: S&P Global, International Energy Agency (IEA)

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The MTM scenario is comparable to other recognized global climate scenarios, such as the IEA's Net Zero by 2050 scenario. The MTM case emphasizes practicality. It is built on the assumption that vast, complex industrial infrastructures of what was an $88 trillion world economy in 2021 will take time to adjust. As a result, emissions reductions lag in the first decade compared with the IEA model, then accelerate to reach net-zero CO_2 emissions by 2050. Negative CO_2 emissions compensate for the remaining emissions from other greenhouse gases (GHG) in order to achieve net zero for total GHG emissions. The figure above compares these two models. The end result is the same.

S&P Global's other two current scenarios are Green Rules and Inflection. They represent "worlds" that do not implement net zero by 2050, and where copper demand still increases but reaches a level slightly lower in 2050 than in the MTM scenario.

Global ambitions: Net zero by 2050 goals are increasingly adopted by countries around the world

The Paris Agreement during the 2015 United Nations Climate Change Conference (COP21) entered into force in November 2016 between 196 countries. Its goal is to "limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels."[20] In practical

20. United Nations Framework Convention on Climate Change, "The Paris Agreement," https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, accessed 21 June 2022.

terms, it requires that countries curb their emissions as quickly as possible to achieve carbon neutrality by midcentury. That objective was reinforced at COP26 in Glasgow, in 2021.

United States: Decarbonization goals set to drive up copper demand

The United States has announced decarbonization goals that would drive copper demand up in the United States. This study assumes that all the necessary regulatory and legislative policies and programs necessary to adopt and achieve these goals will be implemented—which would drive copper demand in the manner described in this report. In its *Long-term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* published in November 2021, the United States laid out specific goals for how the United States would limit global warming to 1.5 degrees Celsius, including 100% decarbonized electricity by 2035 and 50% zero-emission vehicle (ZEV) sales by 2030.

These two transformations are critical for this study. The technologies supporting them (renewables and battery electric vehicles (BEVs), in particular) have a high copper intensity and are major drivers of the ramp-up in copper demand by 2035.

The US Department of Energy has highlighted the general shortfall of resources, which would include copper. "The anticipated increase in demand of clean energy technologies such as wind turbines, solar PV, nuclear reactors, energy storage, and fuel cells and electrolyzers needed to support US climate and competitiveness goals [...] has raised concerns about future availability of raw materials."[21]

Key US decarbonization goals from the US administration

1	2	3
Net zero carbon emissions by 2050	**100%** clean electricity by 2035, including carbon capture and storage (CCS)	**50%** of new light-duty vehicles sales to be zero emissions by 2030

Source: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, White House, 2021. © 2022 S&P Global: 2006021

European Union: Ever more ambitious climate goals will increase the need for copper

The European Union set out similar ambitious goals for net zero in 2019 in its European Green Deal with the aim of "reducing net greenhouse gas emissions by at least 55% by 2030" and reaching climate neutral by 2050.

To support its Green Deal, the European Commission has developed its Taxonomy that identifies favored energy sources and seeks to direct the allocation of capital for energy investment. Most

21. US Department of Energy, America's *Strategy to Secure the Supply Chain for a Robust Clean Energy Transition, U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"*, 24 February 2022.

recently, in response to Russia's war in Ukraine, the Commission has proposed the REPowerEU plan, to make Europe independent from Russian fossil fuels before 2030. This plan includes further accelerating renewables deployment and electrification of the economy.[22]

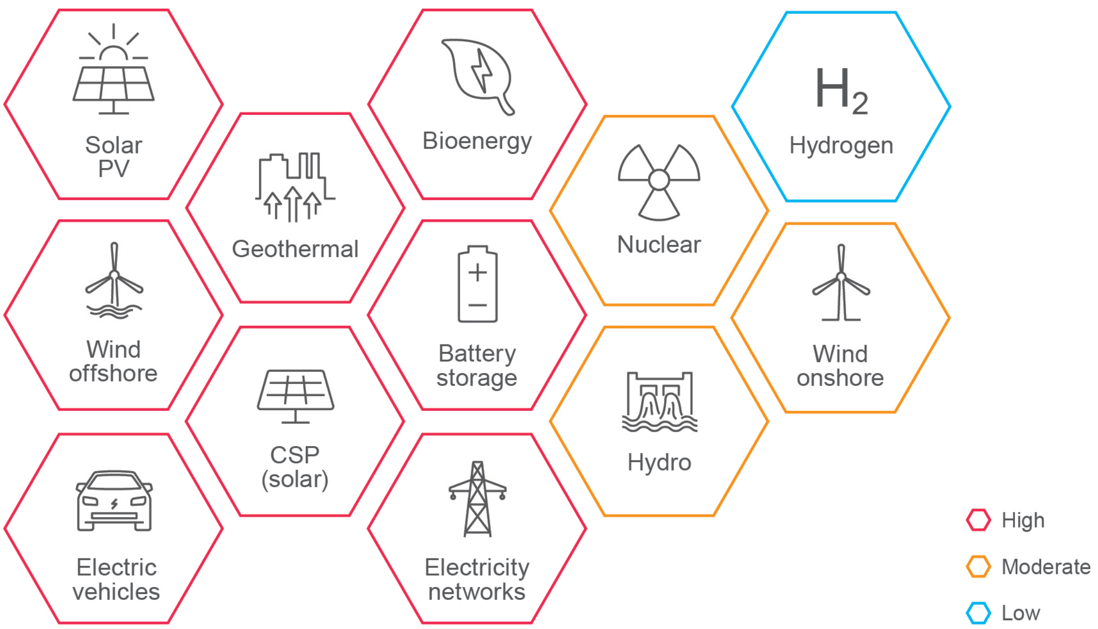
Copper intensity in key energy transition technologies

To meet the transition ambition, the deployment of new technologies that rely on electrification and not fossil fuels is required on a global scale. Energy transition–related technologies have a higher mineral intensity than traditional automotive and power technologies. In addition, the electrification of the economy will require major investments in modernizing and expanding the power grid infrastructure, which requires additional copper. Minerals intensity, and in particular copper intensity, is key to understanding the impact of achieving Net-Zero Emissions by 2050 on copper demand.

Current copper intensity by technology

Copper is nearly unrivaled as an efficient electrical and thermal conductor, and as such will be one of the most important minerals for energy transition (only silver is better as a conductor, as noted earlier, but its costs preclude it from a role in electrification). As shown in the figure below, copper content is particularly high in several key technologies required for decarbonization, such as solar PV, wind, batteries, and EVs. Moreover, the more traditional applications relying heavily on copper such as electricity networks (both for power transmission and distribution) will also

Presence of copper in energy transition technologies



Note: CSP = concentrated solar power. Increased grid transmission and distribution investments are not considered in the copper intensity assessment of each technology as it has been modeled separately. Increased copper demand from power transmission and distribution reflects these requirements.
Source: S&P Global

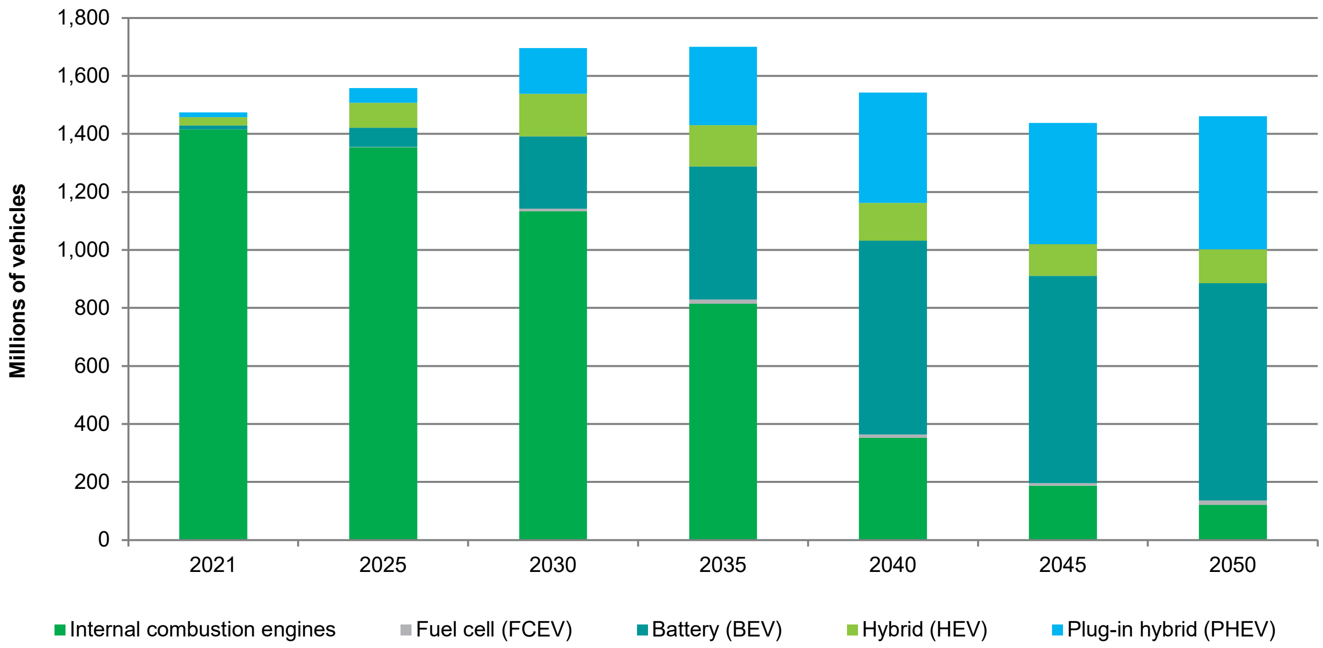
22. REPowerEU Plan, communication from the Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee, and the Committee of the Regions, 18 May 2022.

see an expansion in the coming decades. Key technologies for energy transition will be discussed in detail below.

Automotive sector

In the automotive sector, achieving net-zero ambitions requires transitioning from conventional internal combustion engine vehicles to low-emission vehicles or ZEVs. The key technologies for ZEVs are BEVs and fuel-cell electric vehicles (FCEVs), which function with hydrogen. Low-emission vehicles are primarily hybrid vehicles, including plug-in hybrid vehicles, and combine an internal combustion engine and a battery.[23] Many automakers are staking out positions to go all-EVs by 2035 and, in some cases, by 2030. In the MTM scenario, the global light-duty fleet is expected to continue to grow into the 2030s, before starting to shrink with increased penetration of autonomous vehicles, ride sharing, and car sharing, along with renewed support for the development of public transportation. It should be noted that in the other scenarios the global fleet continues to expand after 2050, which would increase copper demand even further. In the MTM scenario, hybrids and BEVs comprise the majority of the global vehicle fleet from 2040 onward. FCEVs are expected to represent only a small share of the light-duty vehicle market but have a higher penetration in the heavy-duty vehicle market.

Global light-duty vehicle fleet by powertrain



Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions.
Source: S&P Global

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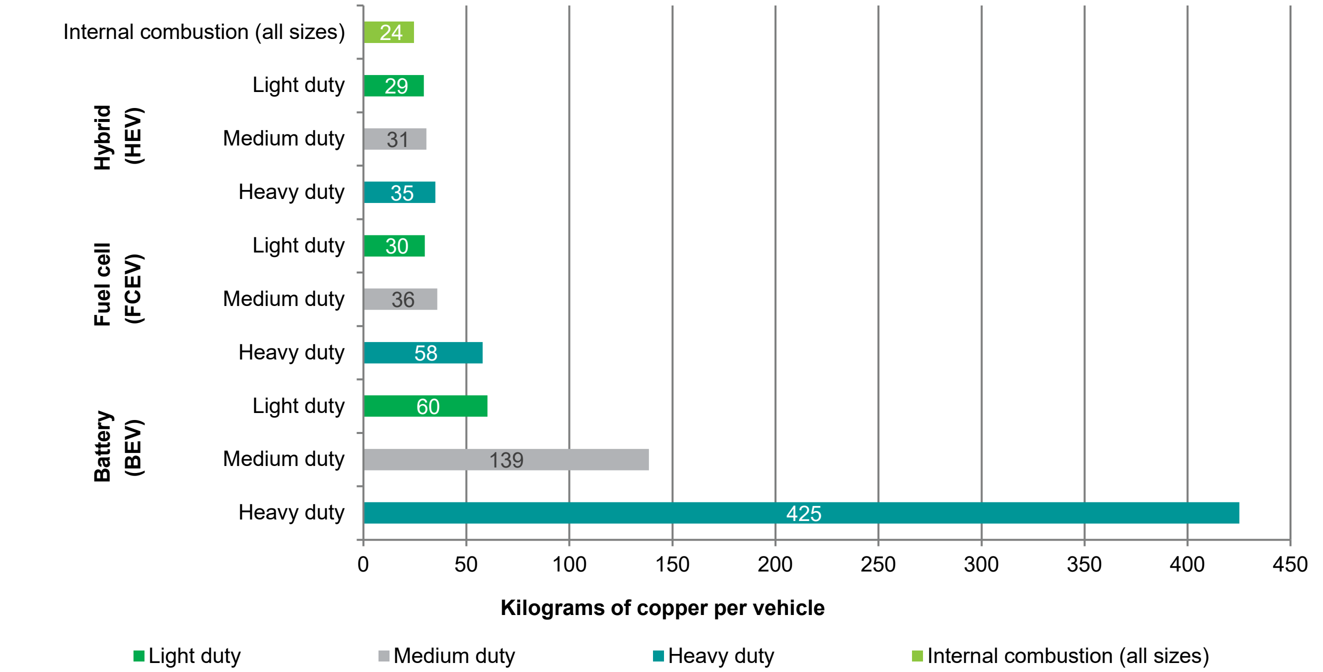
Analysis by S&P Global's Mobility group currently concludes that building a BEV currently requires about 2.5 times more copper than conventional internal combustion engine cars.[24] Copper is present in the internal wiring (harnesses), capacitors (battery packs), and electric

23. Colloquially, the term electric vehicles or EVs refers to fully or partially electrified vehicles, including BEVs, hybrids (HEVs and PHEVs), and FCEVs.

24. S&P Global analysis based on current practices and available technologies within the automotive industry as of the writing of this report.

motors (e-motors). EVs cannot function without copper. The following chart provides an estimate of the copper content per vehicle type for key technologies.

Current copper content by vehicle for key powertrains



Source: S&P Global analysis, S&P Global Mobility group

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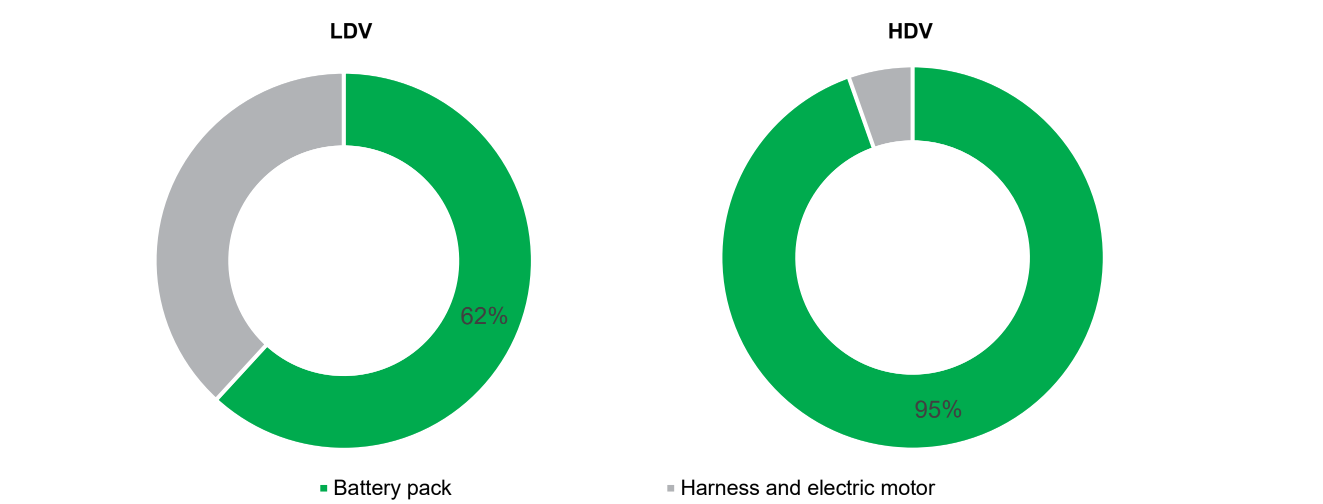
The copper required for the collectors inside the battery packs of BEVs, as well as the e-motor itself, are the main drivers of increased copper demand. More BEVs mean more battery packs and e-motors. This is magnified in medium-duty vehicles and heavy-duty vehicles, where the size of the battery pack required is much larger to maintain a sufficient range. For instance, a Class 8 truck, a

Copper demand in BEVs



Note: HDV = heavy-duty vehicle; LDV = light-duty vehicle; BEV = battery electric vehicle.
Source: S&P Global analysis

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typical 18-wheeler, will require a battery about 11 times the size of a personal car battery. As a result, the battery pack is responsible for over 90% of copper demand in larger vehicles. The following figure illustrates the copper demand by component in a light-duty versus a heavy-duty vehicle.

The electrification of the transport fleet will also require building a global charging infrastructure that does not exist today. Copper requirements for BEV chargers are dependent on the charging level of the stations considered. S&P Global has estimated copper demand to range between about 1 kg of copper for a Level 2 charger (6–8 hours to charge) to about 4.5 kg of copper for a Level 3 charger (mostly charged in less than 60 minutes). Charging infrastructure is expected to grow with the BEV fleet, estimated at about 2.8 BEV per installed charger. Comparing the copper requirement for a single vehicle (60 kg/vehicle) to the charger (5 kg/charger, with 2–3 vehicles per charger) indicates that chargers themselves will represent about 3% of the copper required for a BEV. This estimate does not include the additional power distribution investment required to support the charging infrastructure, discussed below.

Power transmission and distribution (T&D)

Copper is the material of choice in nearly all types of electrical wiring. In the T&D sector, copper is primarily used in power distribution and transformers, in particular for underground and subsea lines. The transmission sector has preferred aluminum for high-voltage overhead lines, limiting the use of copper in this sector outside of specific countries like China. Copper use in T&D applications represents close to 20% of current copper demand.

Achieving Net-Zero Emissions by 2050 will require investments in T&D infrastructure to more than double between today and 2040. This required increase will be driven by several factors, including

- **Penetration of distributed renewable electricity generation.** Renewables penetration will require an increase in T&D infrastructure to support the increased intermittency and the distributed nature of generation, composed of a large number of small facilities typically remotely located, as opposed to a smaller number of conventional large-scale generation plants usually sited closer to where the power is needed. Residential and commercial installation will further increase the need for distribution investment to manage the flow of power back to the grid.

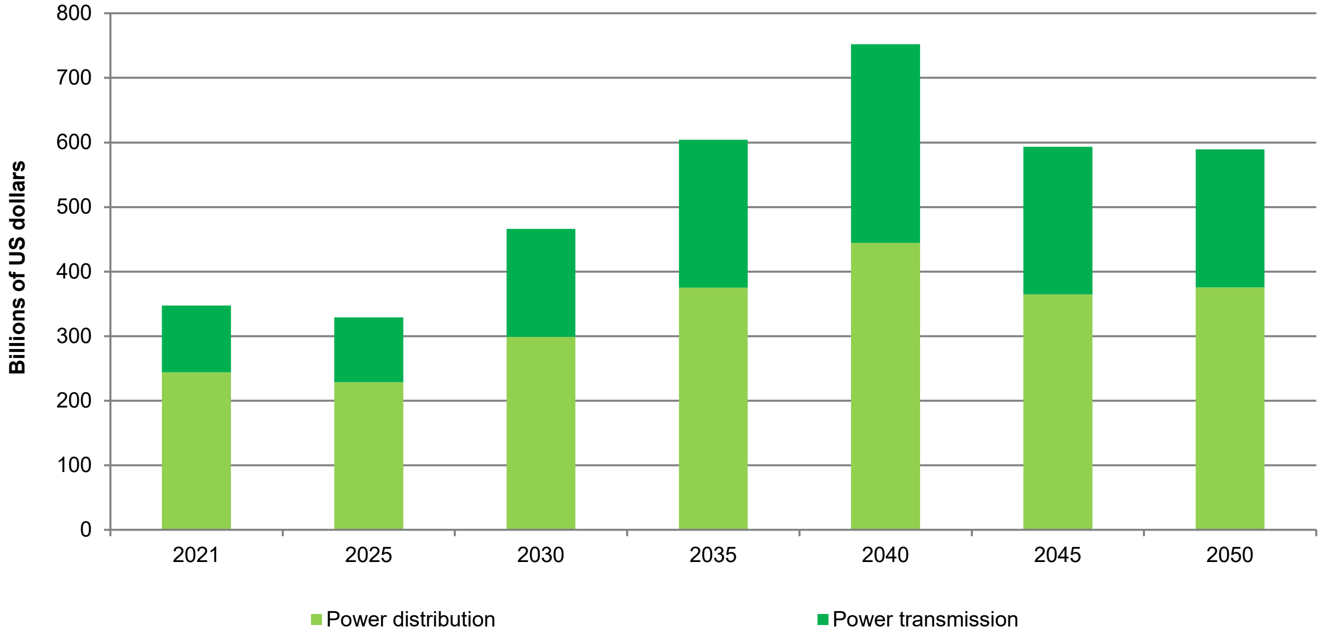
- **Infrastructure to support the electrification of the economy.** The electrification of the transportation sector will require significant investment in distribution infrastructure, which would serve as the foundation of the required charging infrastructure.

- **Replacement of aging lines by upgraded infrastructure.** Smart grids will play a critical role in accommodating increased renewables penetration and electrification. This will require the upgrade of a significant portion of existing infrastructure, representing around one-third of projected investments in T&D infrastructure.

- **Improving resilience in the face of disruptions.** Hardening the entire electricity generation and transmission system against physical and cyber threats has moved to the fore for the power industry.

The following figure shows the global outlook for investment in T&D in the MTM case. These investment numbers include required investments for the grid interconnection of generation technologies (increased interconnection costs from distributed renewable electricity), grid strengthening and replacement of aging lines, and overall T&D network expansion to support the electrification of the economy globally.

Global investments in power transmission and distribution



Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions.
Source: S&P Global

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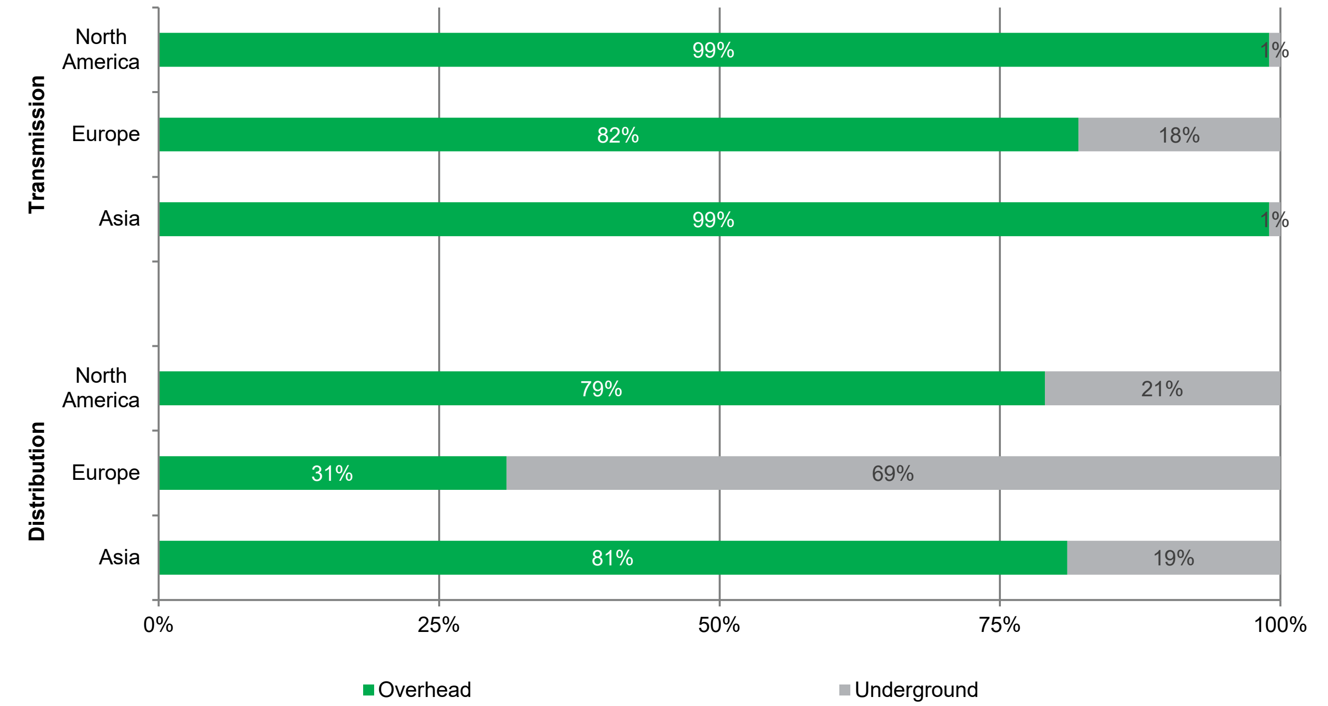
The scenario forecasts T&D investment to more than double between 2021 and 2035. From 2021 to 2025, however, the reduction of overall investment is primarily driven by the assumption of a decrease in copper prices from their current record-high levels. As we will illustrate, this assumption would be compromised by a likely shortage of supply. Despite this reduction in total investments, copper demand for T&D infrastructure is still expected to increase from approximately 4.7 MMt in 2021 to approximately 4.9 MMt in 2025, before reaching 8.7 MMt/y in 2040.

Some of the increase in T&D infrastructure will not be supplied by copper. Aluminum can play the role of substitute in certain cases. In general, aluminum is increasingly privileged for overhead T&D, as it is relatively cheaper and more lightweight than copper. However, aluminum does have increased maintenance requirements and lower technical properties for electrical conduction compared with copper (lower conductivity entails larger cables, and higher corrosion issues). Currently, aluminum production can be more carbon intensive than copper production. These physical characteristics mean that copper remains a material of choice for underground and subsea lines, where technical specification and maintenance play a larger role. Aluminum is also not ideal for transformers.

There are also geographical discrepancies in copper usage in T&D, linked to both the ratio of overhead and underground lines, as well as varying regulatory standards. For instance, China and Japan are currently favoring the use of copper in their electrical network over aluminum, although aluminum is progressively being introduced in these markets as well due to building code changes to allow for the greater use of aluminum wiring in residential construction—a move prompted by developers because of the high cost of copper.

The following figure provides the distribution of underground and overhead powerlines by region, highlighting the prevalence of overhead lines in both Asia and North America in comparison with Europe.

Estimated grid mix in key regions

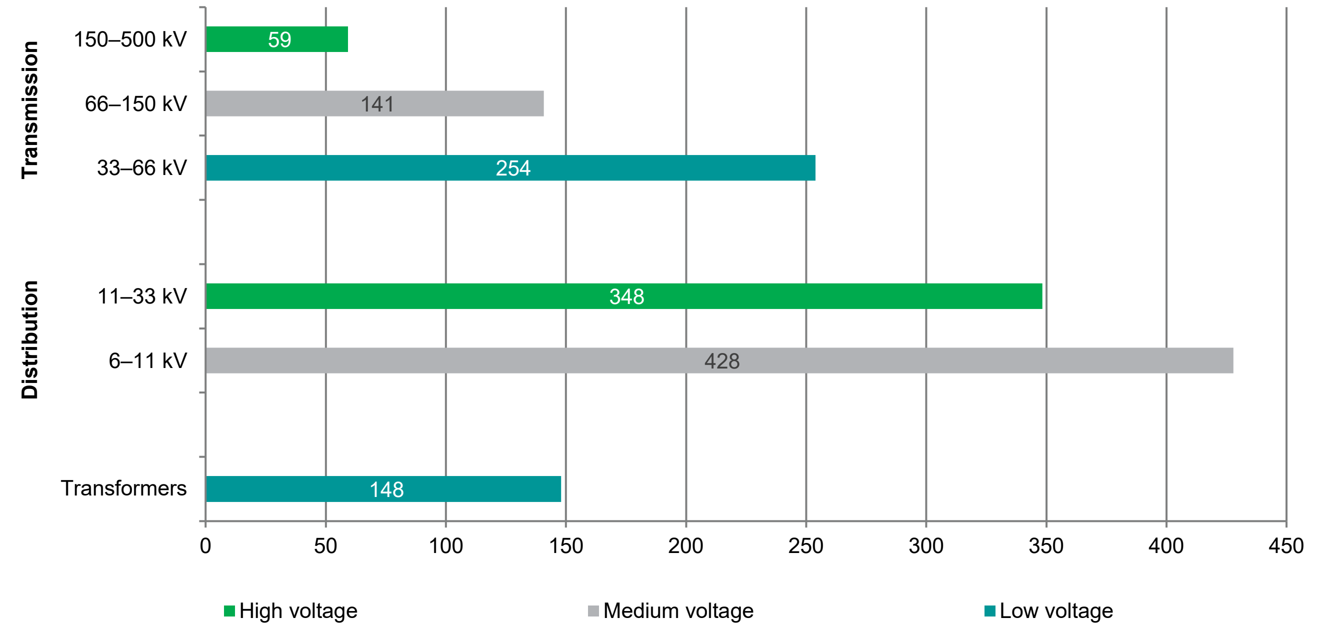


Source: S&P Global analysis, State Grid Corporation of China, National Grid, American Electric Power, US Department of Homeland Security © 2022 S&P Global

The current trend in the industry to bury power lines could favor increased copper use in some geographies, as weather hazards linked to power T&D (e.g., recent major wildfires in California, or the increasing occurrence of hurricanes in the US Gulf Coast) have become a major risk concern for some utilities and an overall driver for greater resilience.

Copper usage by voltage rating and type of application varies significantly, with the distribution sector the main driver of copper use in power T&D. Lower voltage distribution has the highest copper intensity on a kilometer (km) and megawatt (MW) basis.

Copper demand in transmission and distribution systems



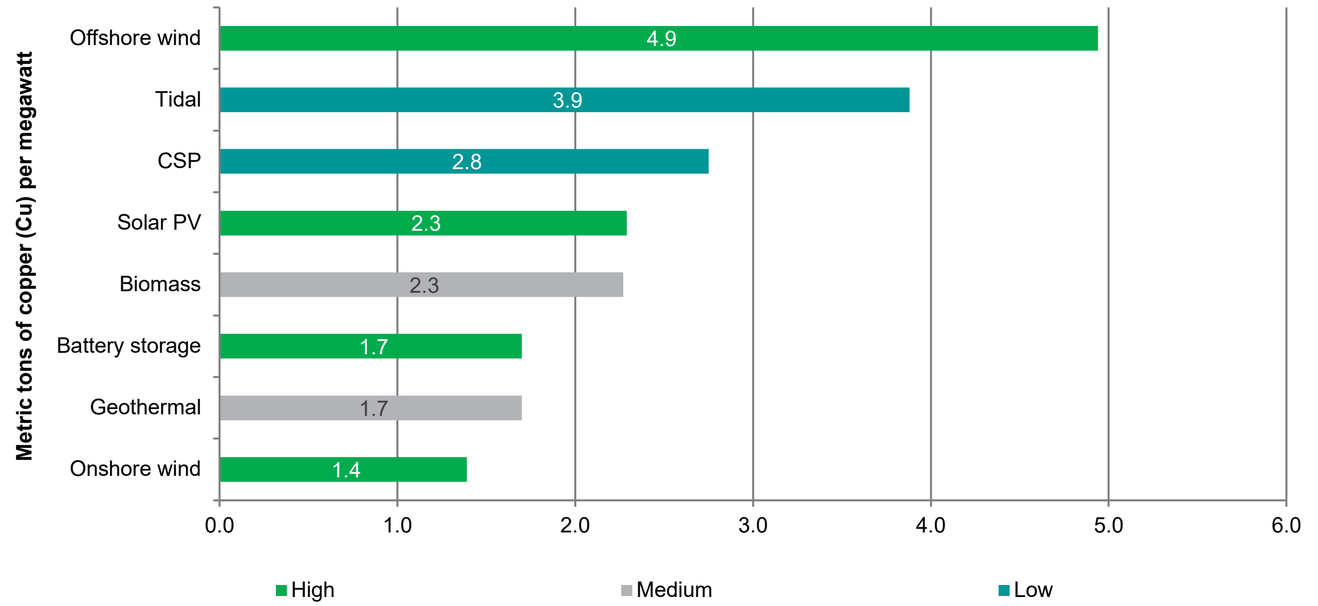
Note: Kilograms of copper per kilometer and megawatt (kg/(km or MW) for transmission and distribution. Kilograms of copper per megavolt-ampere (kg/MVA) for transformers.

Source: S&P Global analysis, State Grid Corporation of China, National Grid, American Electric Power, US Department of Homeland Security

Power generation sector

In power generation, Net-Zero Emissions by 2050 will require large capacity additions of clean power technologies and battery storage to replace conventional fossil fuel–based generation. The shift toward such technologies as solar PV and offshore wind—which consume both 2 and 5 times more copper per megawatt of installed capacity than traditional power generation technologies such as coal or natural gas—will generate an increase in copper demand in this end market. The amount of copper required will depend heavily on the type of technology implemented. The figure below provides current estimates of copper intensity per unit of installed capacity (in megawatts) by technology.

Copper content per megawatt of installed capacity—excluding transmission[1]



1. Except for farm-to-the-shorelines for offshore wind.
Note: Relative future capacity additions: high = over 1,000 GW of capacity additions (globally; cumulative); medium = 200–1,000 GW; low = below 200 GW. CSP = concentrated solar power; PV = photovoltaic.
Source: S&P Global analysis

- **Offshore wind** is the most copper-intensive renewable power technology. Direct-drive turbines (favored for offshore use because of lower maintenance) are more copper intensive than gearboxes, plus the transmission lines from a wind farm to the shore are relatively long. Site cables linking each individual turbine to the offshore substation also represent a significant amount of copper consumption.

- **Solar PV** power requires copper in the PV cells themselves, plant and array wiring, inverters, and modules' cables and connections. Together with relatively high anticipated capacity additions, high copper intensity of solar PV makes it an important component of the copper demand story in the energy transition.

- **Battery storage** (outside of the automotive sector) will drive substantial demand for copper, because of the expected relatively high capacity additions through 2050. Copper content varies by technology, with lithium-iron-phosphate (LFP) batteries (being considered to address other metal challenges, such as nickel) using about 60% more copper on a kilowatt-hour basis compared with nickel-manganese-cobalt (NMC) batteries, because of the inherently lower energy density of the LFP chemistry.[25]

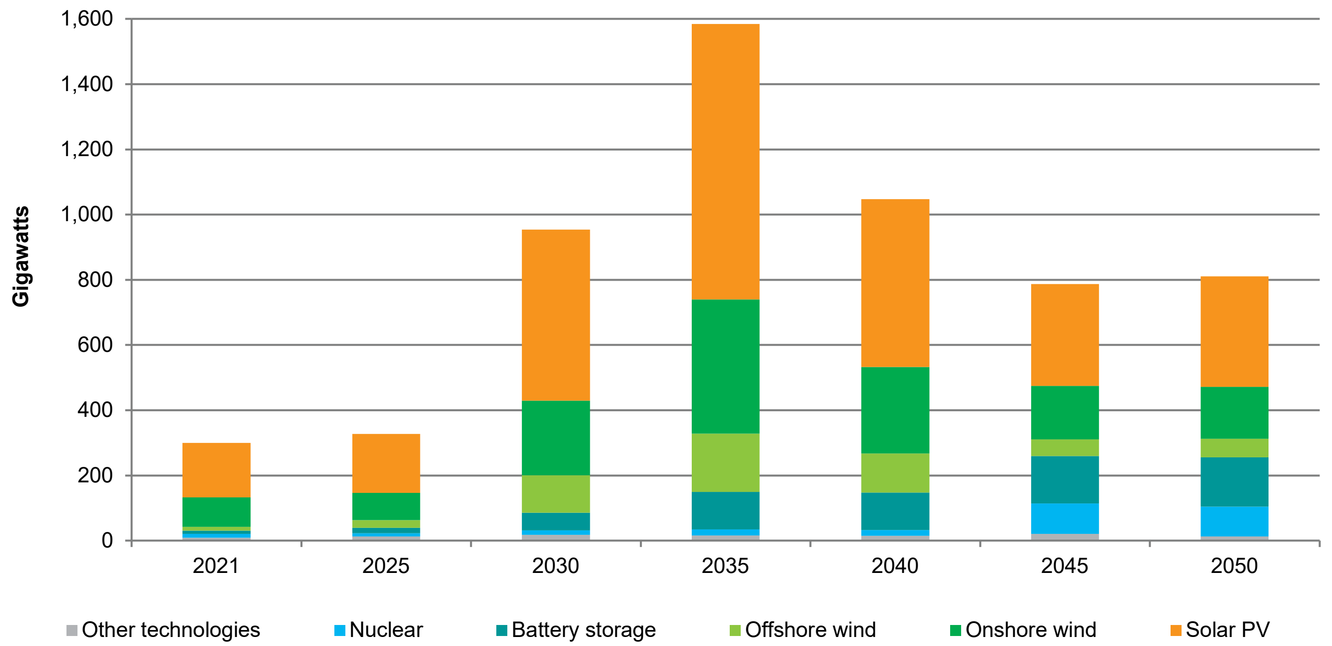
- **Onshore wind** copper intensity is lower than other renewable generation technologies but still represents a large demand source given expected capacity additions. Copper use in this technology comes largely from site cables connecting individual turbines and the turbines themselves.

25. See Appendix B for details.

- **Tidal and concentrated solar** are also highly copper intensive but are not anticipated to be widely deployed in the coming decades.

The projected installed capacity for renewable power generation technologies in the MTM is largely driven by growth in the solar PV and wind (onshore and offshore) capacity through 2035, with battery storage taking an increasing role toward the later part of the forecast. Capacity additions peak at over 1,500 GW in 2035. This initial ramp-up is critical for the decarbonization of the power sector to stay on track for the Net-Zero Emissions by 2050 goal.

Global capacity additions by power technology



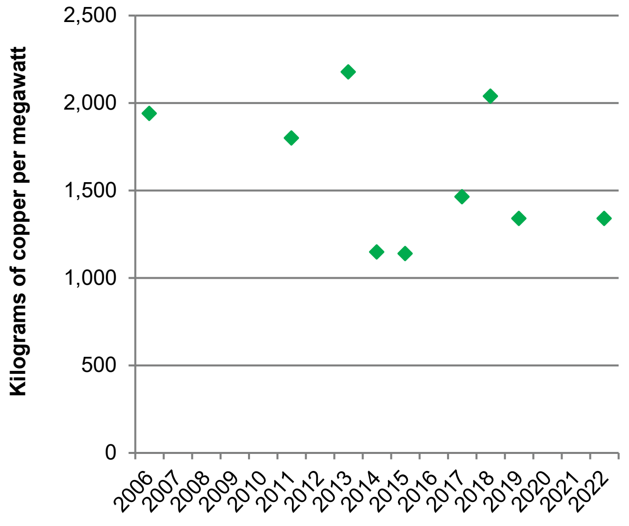
Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. PV = photovoltaic.
Source: S&P Global

Efficiency gains and substitution trends

This study's presentation of copper intensity estimates how much copper is required to build a unit or certain amount of capacity for each technology in the present day. As technologies continue to improve, a downward trend in copper intensity across all energy transition technologies—driven by efficiency improvements and mineral substitution, when technically and economically viable—is anticipated to occur.

The figures below provide examples of historical trends in the onshore wind and solar PV technologies.

Copper intensity in onshore wind turbines



Source: Vestas Lifecycle assessments

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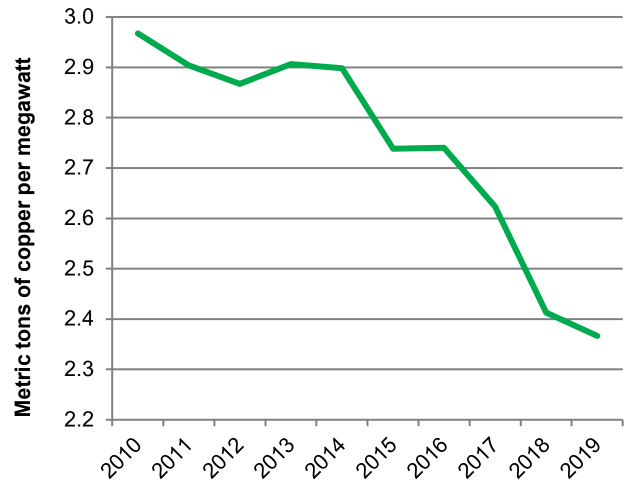
Copper intensity in solar PV



Note: PV = photovoltaics.
Source: S&P Global analysis

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Improved efficiency in the use of copper is the result of a combination of factors:

- Improved engineering and reduction of copper use in some applications
- Economies of scale, as the average size of installation has increased (e.g., the average turbine size for wind has been steadily increasing, however, requiring a lower amount of copper per power capacity [MW])
- Substitution of copper use to other metals, especially aluminum

All reported results assume efficiency improvements to continue at similar rates throughout the forecast. However, it should be noted that these efficiency improvements will eventually reach limits, some of which may happen during the forecast period. Physical properties will constrain the reduction of copper use, as explained further below. This has not been modeled as part of this report. Similarly, an additional constraint in the offshore wind segment is included in the forecast: given that the best sites may be increasingly taken, an increase of the sites' average distance to shore is included in the forecast. This mechanically increases the copper required for subsea transmission lines to shore.

Substitution of copper use to aluminum has been the primary driver of reduced copper use in certain sectors, for electrical wiring in particular. Increased substitution will continue in T&D but will hit technical and economic limitations (see the discussion below). Alternative materials in automotive will also reduce copper intensity in EVs. According to research commissioned by the International Copper Association, copper substitution has represented about 290,000 metric tons per annum of demand between 2018 and 2020, representing less than 1% of overall demand, and is projected to increase and stabilize at around 460,000 metric tons per annum (1.3% of overall demand) in the next five years.[26]

Several key factors will eventually limit the amount of copper that can be substituted in certain applications:

- **Conductivity and space:** copper has the second-highest conductivity of all metals (behind silver, which is cost prohibitive as a substitution). In some applications, this is an absolute requirement. In addition, aluminum's lower conductivity translates into the need for larger cables and the need for more space for the same specifications. In some cases, this presents a technical issue and prevents substitution.

- **Energy efficiency:** copper substitutes tend to have lower efficiency to perform to the same specifications. As energy efficiency gains become front and center in the decarbonization effort, this will support copper usage.

- **High corrosion, friction, and fire resistance:** copper has technical properties that give it advantages in situations where corrosion, friction, or fire risks are a key consideration.

- **Maintenance issues:** aluminum is less ductile (fatigue sets in with breaks possible at stress points when subject to bending), subject to higher oxidation, more sensitive to compression, and has greater thermal expansion and contraction, meaning the connections degrade faster with temperature changes. As a result, aluminum lines require more maintenance than copper lines.

- **Emissions intensity:** aluminum production is a highly carbon-intensive process. This may further restrict substitution as companies are looking to achieve net-zero emission targets.

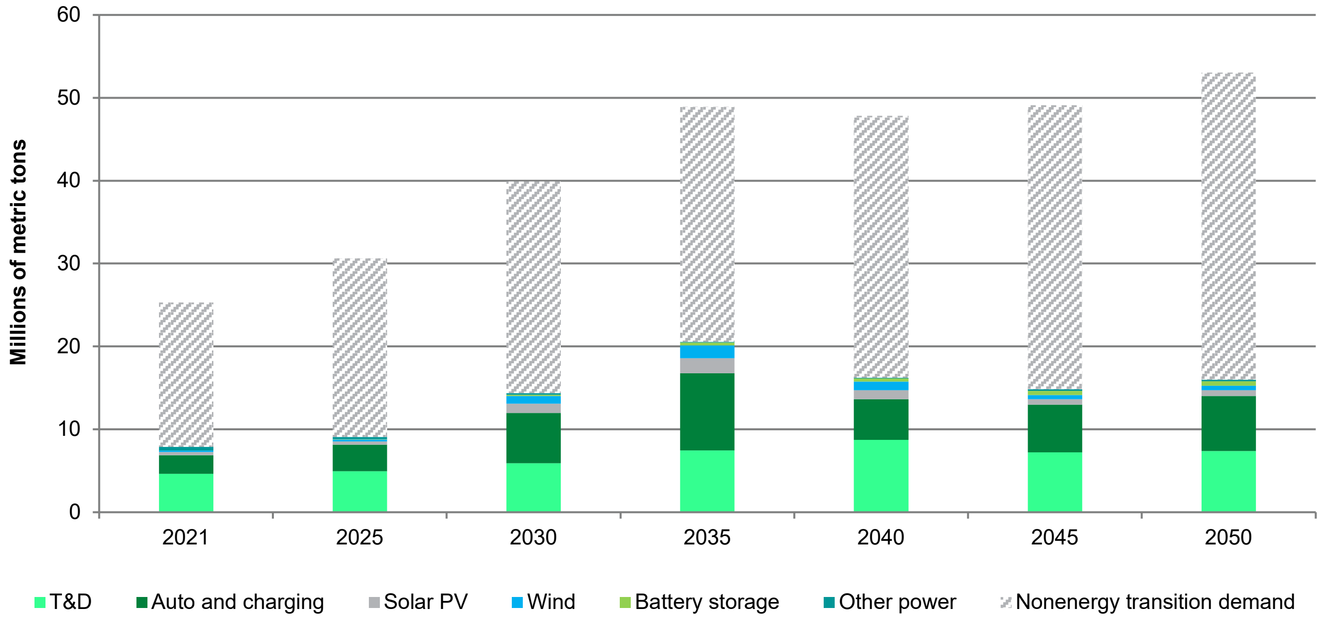
Cost, weight, and theft-risk concerns will continue to drive copper substitution initiatives, but substitution by itself is not expected to bridge the expected supply/demand gap to achieve Net-Zero Emissions by 2050.

Copper demand for energy transition: The next decade is critical

Between today and 2035, achieving the Net-Zero Emissions by 2050 goals will translate into a rapid ramp-up of copper demand, increasing by more than 82% between 2021 and 2035. This ramp-up is largely driven by the required transition to clean vehicles and electrification of the economy.

26. Copper Substitution Survey 2022, DMM Advisory Group.

Global refined copper usage



Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. T&D = transmission and distribution; PV = photovoltaics; other power includes conventional generation (coal, gas, oil, and nuclear), geothermal, biomass, waste, concentrated solar power, and tidal.
Source: S&P Global analysis

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The power and automotive share of global copper demand grows from 31% to 42% of the total, driven by the rapid electrification of the economy. The automotive sector will be the biggest driver of copper demand through 2035, growing from 2.2 MMt/y in 2021 to 9.3 MMt/y in 2035. The electrification of the transport fleet is expected to have the largest impact on copper demand as EV sales increase rapidly to meet the Net-Zero Emissions by 2050 goals.

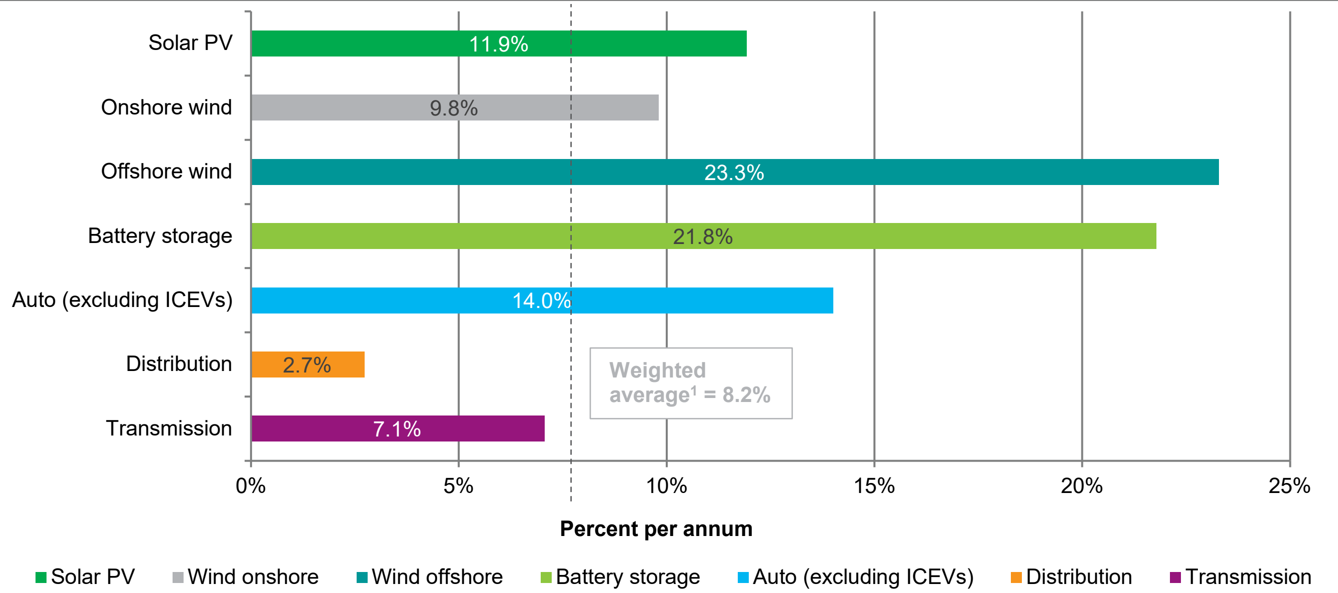
Copper demand for T&D represents the second-largest sector in terms of volume, growing from about 4.7 MMt/y in 2021 to 7.5 MMt/y in 2035. The historical role of copper is expected to continue to support the expansion of the T&D infrastructure, largely driven by copper needs in the distribution sector, as well as for transformers.

Finally, in the power generation sector, solar PV, wind, and battery technologies combined grow from about 0.6 MMt/y in 2021 to 3.7 MMt/y—a smaller impact in absolute volume, but the fastest relative growth rate overall.

Copper demand growth by technology

As described above, growth in copper demand will vary greatly by technology. The T&D sector has been relying on copper for decades, and it will continue to play a key role. Newer technologies such as solar PV, wind, and particularly battery storage constitute new copper uses and will see double-digit growth rates for copper demand in the next decade. The following figure shows the estimated growth rate for copper demand between 2021 and 2035 for selected technologies.

Gross copper demand compound annual growth rate for key energy transition applications (2021–35)



1. The weighted average includes all energy technologies analyzed, including CSP, biomass and waste, geothermal, tidal, BEV charging, and transformers, which are not shown on this chart.
NOTE: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. ICEV = internal combustion engine vehicles; PV = photovoltaics; CSP = concentrated solar power.
Source: S&P Global analysis

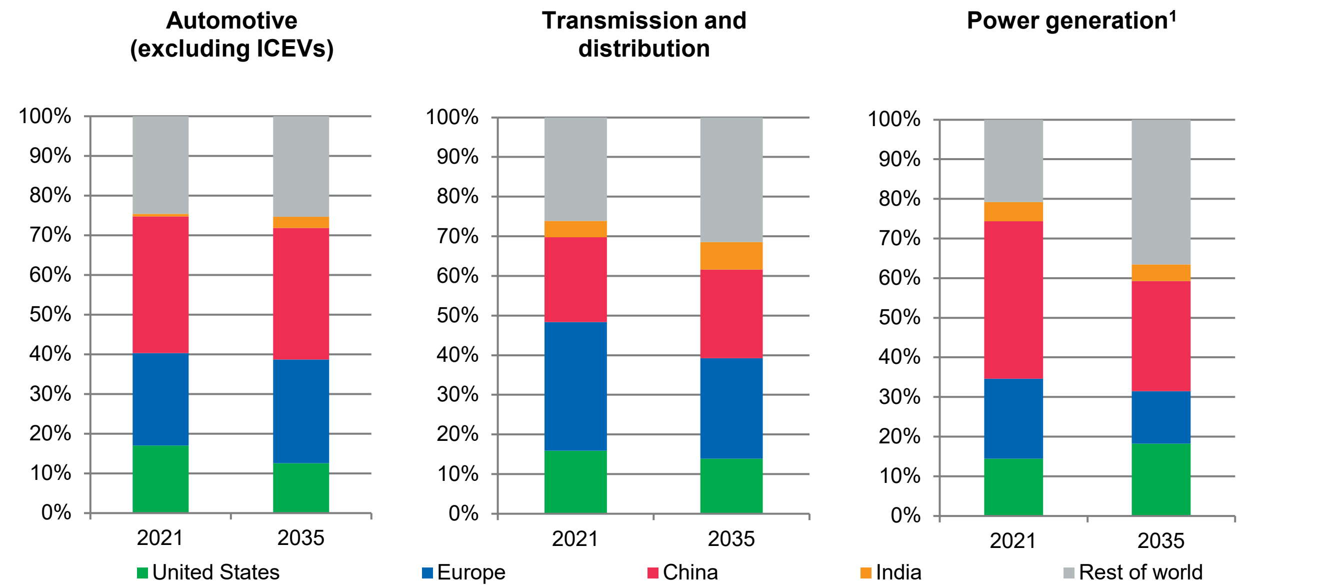
The T&D sector will see single-digit growth rates in copper demand compared with newer energy transition technologies, which will see higher growth in the double digits. As the T&D sector already represents a significant share of global copper demand, lower growth rates in this sector should not mask the fact that T&D will still drive a major increase in the absolute demand for copper.

Battery storage and offshore wind will both see the highest growth rates, illustrating their position as emerging energy transition technologies that did not exist at the commercial scale only 10 years ago.

Regional copper demand view

Demand for copper from the energy transition will not be evenly distributed. It will originate from four key actors: China, Europe, the United States, and, to a lesser extent, India (although India will also represent a significant share of growth in global nonenergy transition copper demand). China is the copper market's center of gravity. It alone will play a critical role in copper markets for decades to come, as the largest, single demand country globally. The figure below illustrates the share of demand from key countries for each of the sector considered in the demand ramp-up to 2035.

Global copper demand for key energy transition sectors by main countries and regions



1. Power generation includes solar technologies (PV and CSP), onshore and offshore wind, tidal, geothermal, biomass and waste, and energy storage.
Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. ICEVs = internal combustion engine vehicles; MMt = million metric tons; PV = photovoltaics; CSP = concentrated solar power.
Source: S&P Global analysis

The critical role of China

Globally, China is the largest user of copper overall with 54% of global demand in 2021, and a critical actor in the energy transition, representing between one-fourth and one-third of the global demand for these technologies, depending on the sector considered. Despite coming from a continuing reliance on thermal energy and coal in particular, the Chinese government is promoting a new power system based on renewables. The recent announcement of the carbon neutrality goal by 2060 and the 14th Five-Year Plan (FYP) amplify major renewables and low-emissions vehicle buildup (although also emphasizing energy security).

By end-2021, China had about 35% of the global nonhydro renewables installed capacity.[27] It continues to drive the global buildup, both in terms of installed capacity domestically and manufacturing capacity. In addition, around 80% of the global solar PV cell and module manufacturing capacity is located in China currently, underlining its outsized role in energy transition technologies.

On the automotive side, China is promoting the EV market and has cultivated the growth of the country's EV industry with a variety of regulations and incentives. China accounts for over 50% of current global EV production today and holds a similar share of the current world's EV fleet. It now has the most comprehensive supply chain for EVs and is the home for the world's largest battery maker, CATL. It continues to implement key policy changes to further support this development, including China's growing role as an exporter of electric cars.

27. As a comparison, the United States had about 14% of the global non-hydro renewables installed capacity (with 141 GW of wind capacity and 100 GW of solar capacity installed in 2021). Excludes conventional thermal power generation.

The other key players: Europe, the United States, and India

Europe, the United States, and, to a lesser extent, India will be the other major players in the copper market. Collectively with China, the four countries/regions are expected to represent about 70% of global copper demand for energy transition applications by 2035.

In Europe, the European Commission and individual countries have been pushing ambitious decarbonization goals since the 2000s. Europe represents the second-largest copper demand for energy transition applications after China and is expected to play a key role in securing copper supply.

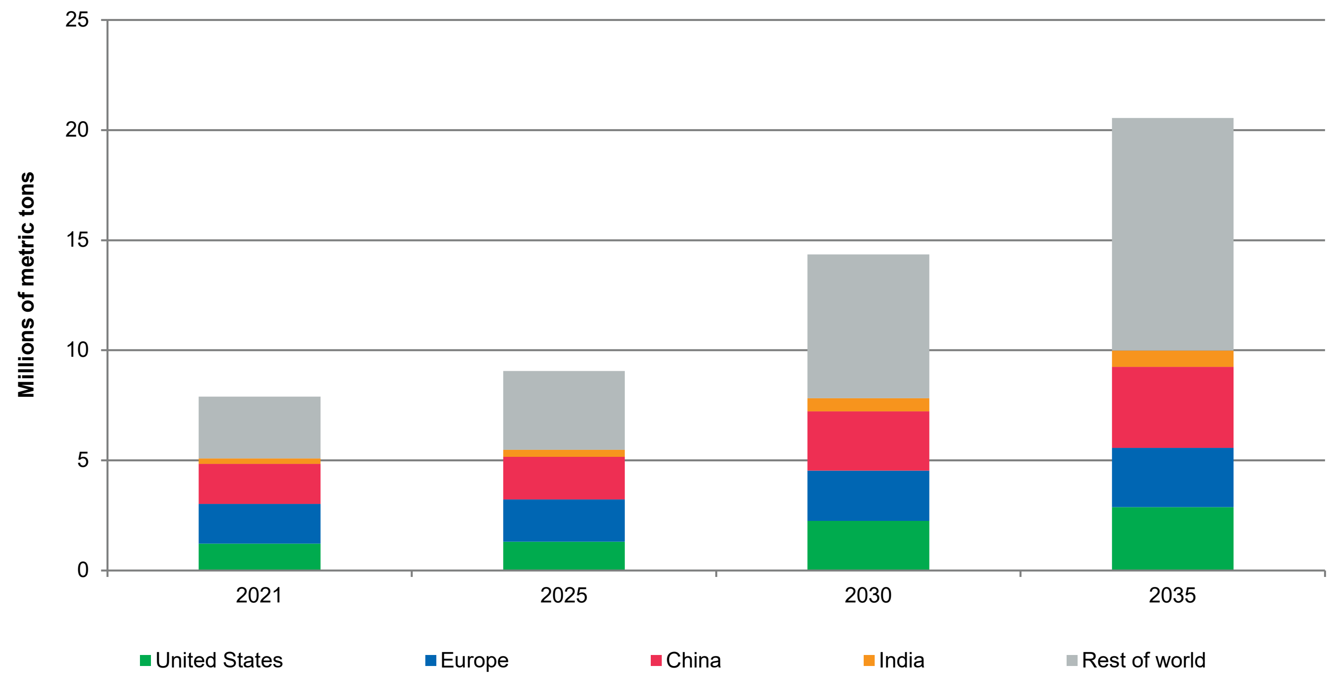
In the United States, 100% clean electricity by 2035 and a rapid electrification of the automotive fleet will drive a rapid increase in copper demand for the United States in this decade.

India has a target of 450 GW of installed renewable capacity by 2030. The country currently remains highly reliant on thermal generation and coal and will continue to use coal-fired generation alongside with renewables to support its strong electricity demand growth. In terms of transportation, India has one of the lowest light-vehicle penetration rates. The government is supporting EV development and penetration, but EV sales will be significantly lower compared with China, the United States, and Europe.

Demographers expect Africa's population to double by 2050 to 2.5 billion people—a quarter of the world's population by that point. Economic growth will be the overall priority. As part of that, Africa will see a strong push toward electrification as well, with the Light Up and Power Africa initiative pushed as part of the New Deal on Energy for Africa, supported by the African Development Bank. The plan is articulated around targets for increases in on-grid generation capacity, on-grid connections, and off-grid generation; and for increased access to clean energy for cooking.

These African initiatives will contribute to the increase in copper demand but will represent a much smaller share of the global demand as they are smaller in scale compared with investments in the United States, China, and Europe (160 GW announced in Africa by 2025 versus about 1,100 GW for the United States, China, and Europe combined between 2020 and 2025 in the MTM scenario). In addition, a significant proportion of generation capacity additions is expected to be installed off-grid, as outlined in the plan above, resulting in lower T&D investment requirements.

Global copper demand for energy transition applications (power and automotive) by key country/region



Source: S&P Global analysis

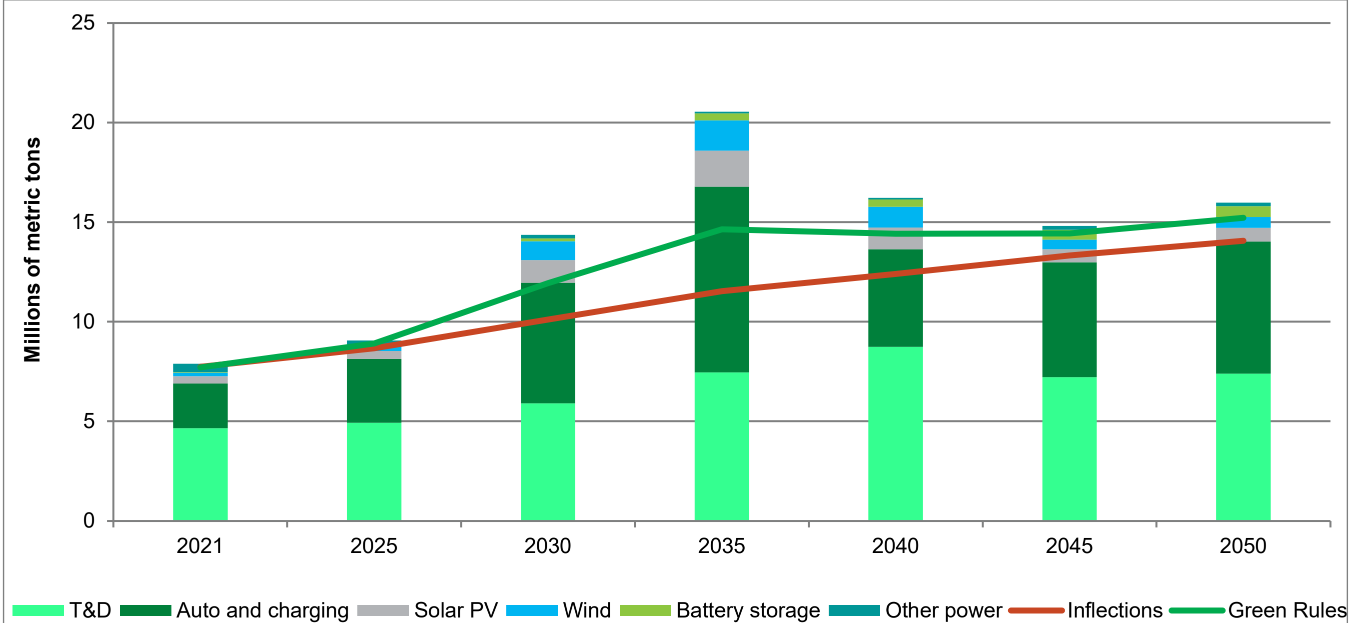
Impact of other scenarios on copper demand

Finally, this analysis of the copper demand for energy transition has been focused on the S&P Global MTM case, which is one of multiple paths that the world could take to decarbonize the global economy by 2050. This study has also examined the impact on copper demand of other potential futures, represented by the S&P Global Inflections and Green Rules scenarios.

The Inflection scenario represents a more restrained future, where hydrocarbon fuels will continue to hold a larger role in the energy system and the economy for some time to come. The Green Rules scenario features strong support for decarbonization that drives governments to implement climate policies and actions. It forecasts robust private investment and innovation that leads to major changes in energy use and supply, moving the world much closer to the Paris Agreement than the Inflections scenario but still not to the level of the MTM. Additional details on each scenario are available in Appendix B. Methodology and approach.

The following figure compares global copper demand from the automotive and copper sectors in the MTM against such demand in the Inflections and Green Rules scenarios. The copper demand estimates embedded in the Inflections and Green Rules scenarios consider the same copper intensity assumptions by technology. It is the automotive sales, fleet composition, power capacity additions, and retirements that vary.

Global copper demand for energy transition applications only (power and automotive)



Note: Based on S&P Global's Multitech Mitigation scenario; US values are adjusted to align with Biden administration's net-zero ambitions. T&D = transmission and distribution; PV = photovoltaics; other power includes conventional generation (coal, gas, oil, and nuclear), geothermal, biomass and waste, concentrated solar power, and tidal power.
Source: S&P Global analysis
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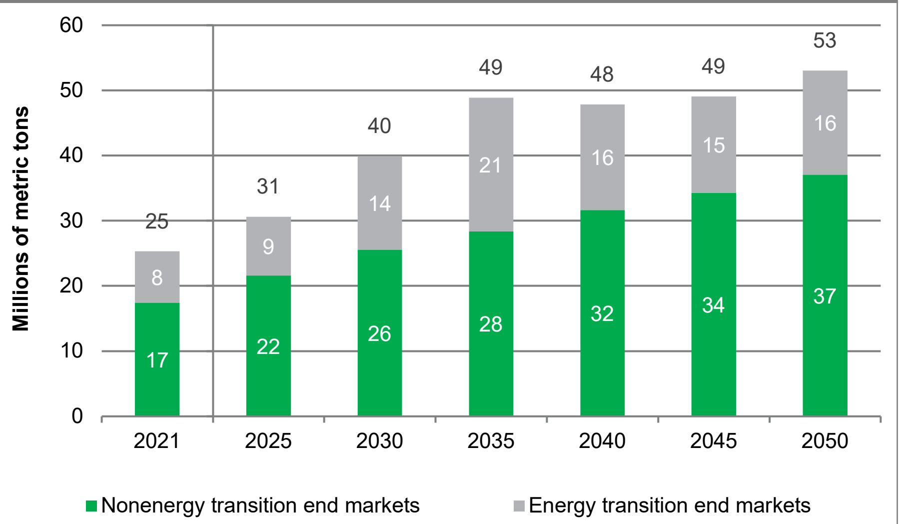
As shown above, while all scenarios point to an increase in global copper demand in the automotive and power sectors, the speed and scale of the ramp-up will differ. Both the Inflections and Green Rules scenarios assume slower decarbonization trends that do not reach the 2050 objective. As a result of the slower deployment of technologies such as EVs and renewables, the high point for energy transition is attained later, while copper demand for energy transition applications reaches similar levels by 2050. The key message from all three outlooks is that a very significant copper demand increase is on the way regardless of the path taken, and that very significant additional supply will be required if the demand is to be met.

Chapter 4. Overall copper demand: Bringing it all together

The drive toward a net-zero emissions global economy will see global refined copper demand growth accelerate as copper use in energy transition technologies ramps up. As this is combined with nonenergy transition copper usage, total copper demand will nearly double from just over 25 MMt in 2021 to nearly 49 MMt in 2035, before reaching 53 MMt in 2050. This will be driven in large part by energy transition end markets.

Breakdown of global refined copper usage



Source: ICSG, S&P Global

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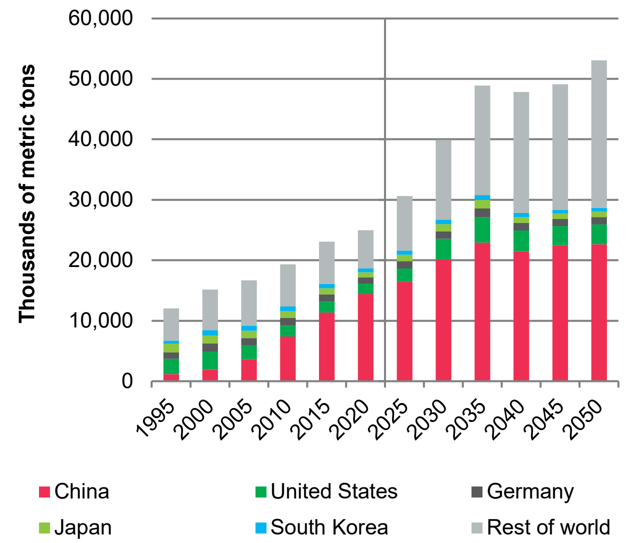
Although demand from energy transition end markets is expected to peak in 2035 at almost 21 MMt and then decline through the late 2040s before marginally increasing in 2050, demand from traditional markets grows continuously between 2020 and 2050 at an average annual growth rate of 2.4%. Combined, total refined copper demand will reach approximately 53 MMt in 2050, more than double 2021 consumption. Energy transition copper demand will grow at a faster rate than nonenergy transition demand through 2050. However, the nonenergy transition end market is the larger segment, still accounting for 58% of the market in 2035 when energy transition copper demand peaks. Because of this, nonenergy transition demand will grow more in total tonnage than energy transition copper demand.

Regardless of source of demand—energy transition or nonenergy transition—the top five refined copper-consuming countries today are dominated by industrialized countries. By 2050, however, only China and the United States will remain in the top five, while India, Vietnam, and Mexico will supplant Germany, Japan, and South Korea in the global rankings. This reflects the industrialization of these emerging economies over the next 30 years, particularly as Mexico and Vietnam shift their manufacturing toward higher value-added manufacturing industries, many of which are copper-intensive. India will see growth, though its development path will continue to focus more heavily on service industries.

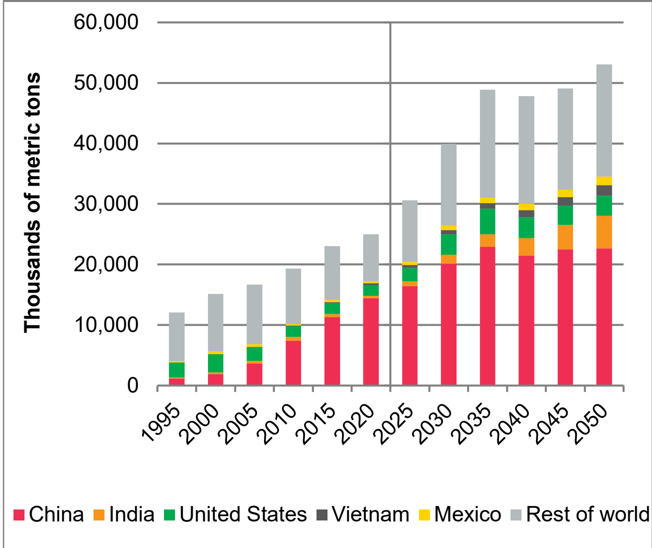
While China will still be the largest user of copper for decades to come, its share of total global demand will decline from a high of 58% in 2020 to 43% by 2050. This reflects both a stated policy goal to shift the economy to focus less on manufacturing and more on services, and the country's demographics. This change in China follows the historical path of other industrialized nations like the United Kingdom, the United States, Germany, Japan, and, most recently, South Korea.

Top copper-consuming regions, 2021



Source: ICSG, S&P Global © 2022 S&P Global

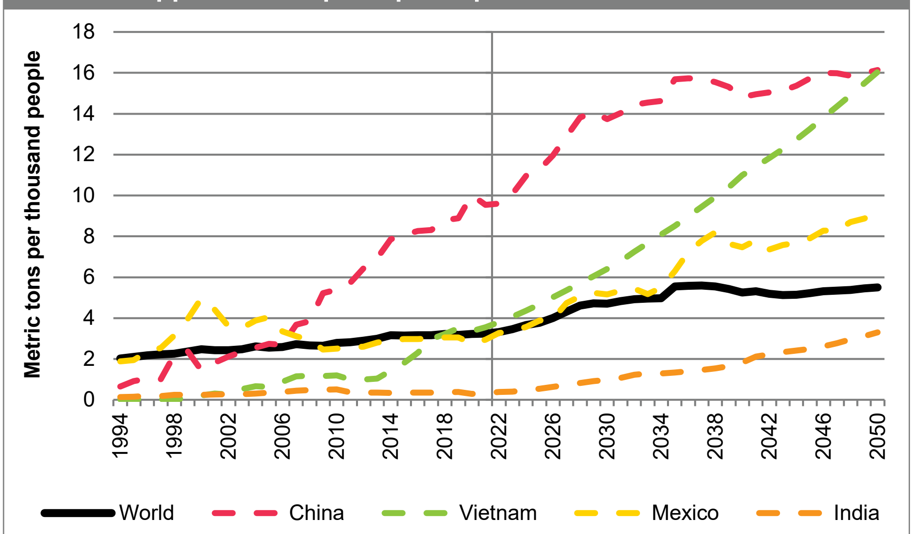
Top copper-consuming regions, 2050



Source: ICSG, S&P Global © 2022 S&P Global

This transition of the Chinese economy away from manufacturing will create circumstances in which some of China's growth in copper demand will shift to other countries. While India and Vietnam are likely to exhibit the most demand growth, other emerging markets such as Brazil and Indonesia will also grow their demand for refined copper.

Refined copper consumption per capita



Source: ICSG, S&P Global © 2022 S&P Global

Because of its large population and steady development, India is likely to emerge as the world's second-largest copper-using economy by 2050; however, its per capita usage will remain lower than that of China, Vietnam, and Mexico. This is in part because services, such as information technology, are already a large share of the Indian economy. As the Indian economy grows and develops, services will remain a large portion of its economy, which is unlikely to see the high levels of natural resource–intensive investment that drove China's development for the past 30 years.

Powered by energy transition–related end markets, total demand for refined copper will swell through 2050, creating a challenge for supply to keep up with these demand ambitions.

Chapter 5. What does this mean for supply?

The preceding sections have quantified how the requirements of the energy transition on top of traditional copper end markets will dramatically increase the overall demand for copper—roughly doubling from current levels by 2035, an unprecedented increase. The amount of copper required between 2022 and 2050 is more than all the copper consumed in the world between 1900 and 2021. But will there be enough supply to meet these demand ambitions?

> Neither scenario presented should be interpreted as a baseline forecast. Rather, they provide a framework for understanding the scale and challenges of meeting the copper supply requirements of Net-Zero Emissions by 2050 whether based on current trends or on a major acceleration.

Demand has been tested against two supply scenarios—High Ambition and Rocky Road. The name “High Ambition” is in the spirit of the oft-repeated phrase that “greater ambition” is needed to achieve 2050 goals. “Rocky Road” reflects all the challenges along the road from excavating rock to finished copper product. Both scenarios make clear that it will be extremely difficult to deliver that scale of supply over the time frame. The annual shortfall in High Ambition is, at its highest, 1.6 MMt in 2035. Meanwhile, the shortfall under Rocky Road is much larger at 9.9 MMt in 2035.

The scenarios describe two different supply responses. In High Ambition, the supply system is put to the test. It is based on performance levels that were achieved in earlier years, plus a major increase in recycling and in which, overall, things go forward without much disruption. Rocky Road represents a continuation of trends as they are today and have been for the past several years of high prices.

There are three possible legs to increasing supply. One is new mines or major expansion of existing mines. The second is higher capacity utilization—that is, increasing output as a percentage of a mine’s total capacity. The third is the “aboveground mine”—recycling—that is extracting copper from discarded batteries, old wiring, and other equipment.

One way to meet the demand growth would be to develop and open new mines. Theoretically, future demand could be met by opening three “tier-one” mines, each producing 300,000 metric tons of copper per year every year for the next 29 years. That would be a monumental and taxing job, and without any precedent historically and costing over $500 billion in today’s dollars. Moreover, it can take more than a decade and a half to develop a new mine. So, growth in capacity comes from a combination of expanding existing mines and progress in opening mines currently under development. This means an average annual increase in capacity of 2.9% from 2021 and 2035, which is a continuation of the recent trend. And then, with an expanded base, it drops to 1.6% between 2036 and 2050.

So, instead, the two scenarios are built around the other variables—utilization and recycling.

Contrasting the scenarios

In High Ambition, output surges as demand pushes ahead. Global capacity utilization increases from 81% in 2021 to 96% by 2035. The driving force is price. When prices are low, high-cost and marginal operations may be idled. Higher prices incentivize working the asset at its maximum, at least for a short period of time, and quickly resolving operational disruptions as much as possible. It also means timely resolution of environmental, operational, and financial issues among companies, governments, labor unions, and local peoples. In other words, this is an optimistic or “everything goes pretty smoothly” scenario. The higher utilization rate implies that technology and efficiency improvements outweigh obstacles such as declining ore grades, water access, supply chain pressures, and other operational issues that will be discussed in more detail in the next chapter.

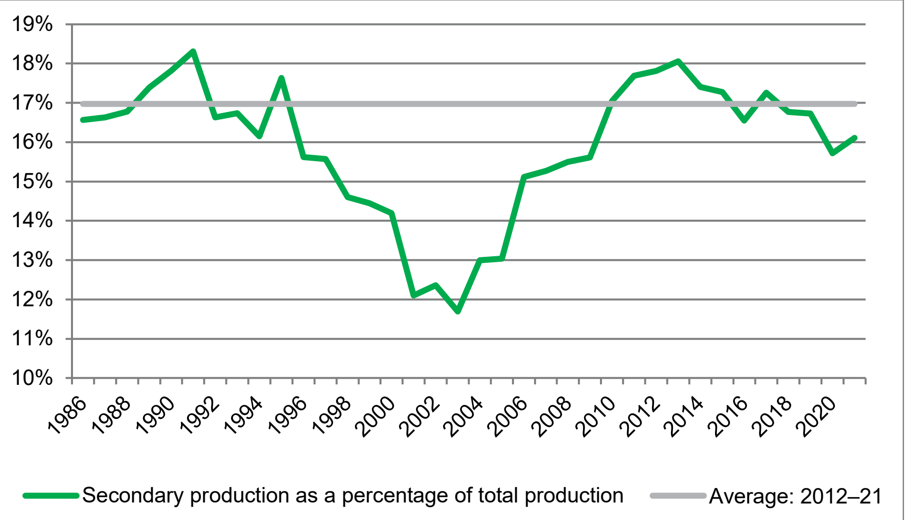
The other side of the equation is recycling, which currently constitutes 17% of total world refined copper supply. Prices incentivize more recycling and innovation in recycling. Two other factors reinforce that trend in this scenario: governments in consuming countries promote and incentivize recycling both to assure copper supply and to reduce the dependence on imports and geopolitically complex supply lines. This is in line with a growing regulatory focus on mandating recycling. After the middle of the 2030s, recycling increases owing to greater supply from energy transition–related end markets—primarily EVs. It will be years before significant numbers of EV batteries are discarded and begin to be recycled. This high recycling rate for EVs, beginning later in the 2030s, is based on the existence of a well-established light-vehicle recycling channels and the emergence of EV battery recycling technologies at scale, which makes “end-of-life” collection less of an issue.

With all this, there is still not enough copper, even in the High Ambition Scenario.

Under this scenario, the maximum annual shortfall would be in the mid-2030s, at 1.6 MMt in 2035. Then the pressures ease because of the increase in recycling and the slowing of growth, particularly in energy transition demand.

Rocky Road reflects the average trend over the past decade. Even as demand grows and prices signal the need for more supplies, pressures everywhere constrain the growth of output, including pressures on supply chains and declining quality of ores from existing mines. Utilization rates remain where they are today, at 84.1%, which is the global average capacity utilization between 2012 and 2021. Recycling remains constant at 17%.

Global recycling rate: 1986–2021



Source: ICSG, S&P Global © 2022 S&P Global

Secondary production (i.e., metal produced from recycled copper) grows continuously in Rocky Road; though as a percentage of total refined copper supply, it remains constant at 17.0%. This is slightly above its 15.4% average recorded between 1995 and 2021. While recycling efforts in the advanced economies are expected to gather force over the next 25 years, the slow shift in the regional composition of demand away from these economies presents a challenge to lifting the global recycle rate in the long term. First, the recycling infrastructure in these emerging markets will remain less well developed, with scrap collection less efficient. However, second, and more important, much of the copper used in the emerging markets over the next 25 years will not have reached the end of its useful life. Even if scrap collection and processing were on par with the advanced economies, the supply of scrap will still be relatively scarce.

Adding it all together, output—both mined and recycled—grows by a compounded annual growth rate of 3.2% through 2035 in Rocky Road. The result is a massive supply gap in 2035 of 9.9 MMt of refined copper—equivalent to 20% of demand projected to be required for a 2050 net-zero world. By way of comparison, the largest shortfall as a percentage of refined copper demand between 1994 and 2021 was 2.5%. These shortfalls in the Rocky Road Scenario would be unprecedented within the copper market and would lead to major reactions.

The reasons that supply does not grow more quickly in the Rocky Road Scenario are multiple. Higher prices lead governments in host countries to seek more revenues and control, which in turn engenders extended negotiations, delays, and domestic political controversies and altogether makes new investment more uncertain. Permitting and legal challenges also impede investment. New environmental restrictions and controversies, along with environmental, social, and governance (ESG) pressures from investors, shift investment and managerial attention and slow growth. Other operational issues intrude, including strikes and turbulent labor relations and what has been identified as declining ore quality from many mines. Issues of local development and controversies with some local populations complicate operations. Supplies chains are strained, and geopolitical stresses introduce new pressures on trade links. While recycling grows in volume, the rate remains constant. Expanded recycling encounters environmental and collection challenges. The trade channels, which supported recycling on a global scale, continue to be hindered, as became clear when China instituted its National Sword Policy, which restricted or complicated the import of a wide range of waste materials including metal scrap.

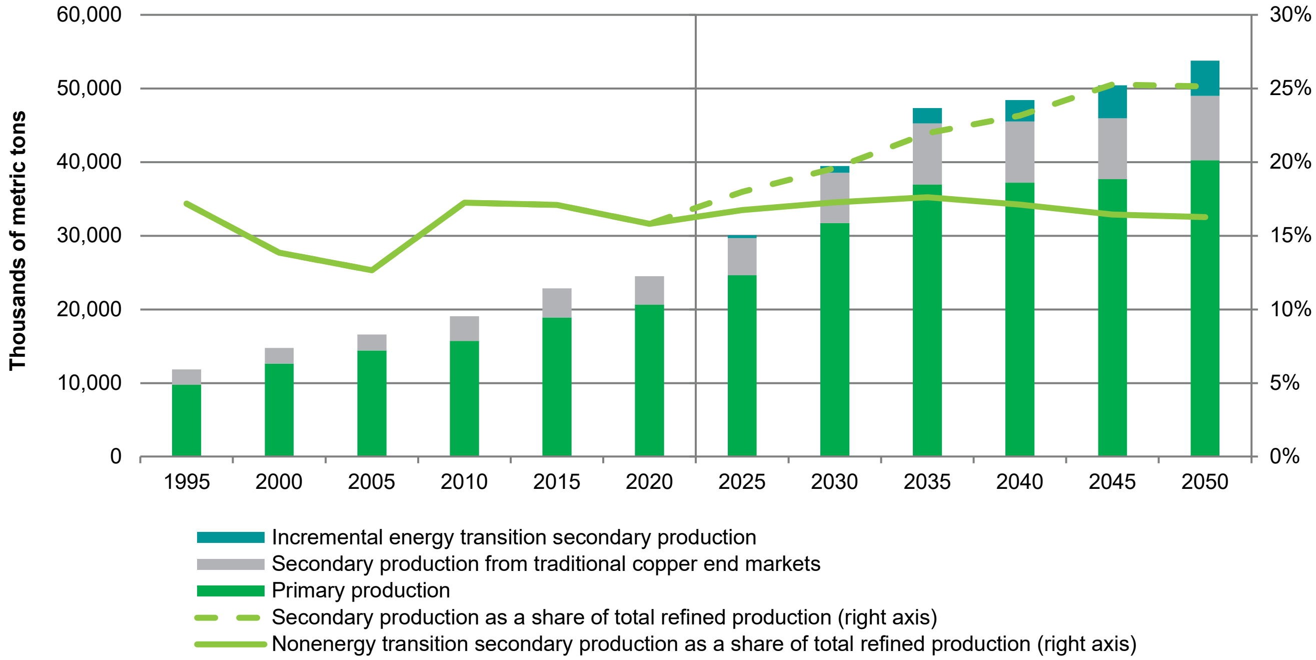
Gaps do not last. They get closed. That is the work of supply and demand. The mismatch between supply and demand ambitions in the Rocky Road Scenario is simply too large and long-lasting to occur. The chronic supply shortfall projected from the mid-2020s through the entire forecast period in the Rocky Road Scenario is untenable and would lead to both supply and demand-side reactions.

Copper supply assumptions	
High Ambition Scenario	**Rocky Road Scenario**
Mine capacity utilization will increase through 2035. The acceleration in demand growth from the energy transition will cause the copper market to tighten, leading to price increases. This scenario assumes capacity utilization will gradually rise through 2035 in response to higher prices. After that, capacity utilization is expected to fall slightly through 2050 as the ramp-up in energy transition demand begins to slow.	**Mine capacity utilization will be held constant.** Global mine capacity utilization will be 84.1% between 2022 and 2050. This represents the global average capacity utilization between 2012 and 2021.
Recycling rates will increase through the medium term but subsequently fall as demand wanes. Recycling in traditional end markets as a percentage of primary production rise through 2035, in response to higher prices and coinciding with peak demand from energy transition end markets. A surplus during the 2040s softens prices, reducing the incentive to recycle. However, recycling from energy transition–related end markets, primarily EVs, will remain high—a lagged effect of EV purchases from before 2035.	**Recycling rates will be held constant.** Recycling rates, or secondary production as a percentage of total refined production, will be held at 17.0% between 2022 and 2050. This represents the global average between 2012 and 2021.
Copper mine capacity growth will slow over time as environmental concerns grow. This study assumes the status quo for copper mine capacity growth, which has decelerated from a compound annual growth rate of 4.9% between 1994 and 2000 to a 2.9% compound annual growth rate between 2001 and 2021. This study assumes mine capacity will grow at a compound annual growth rate of 2.9% between 2021 and 2035, dropping to a compound annual growth rate of 1.6% between 2036 and 2050.	
Global refined primary production as a percentage of mined production will remain constant throughout the forecast period. From 1994 through 2021, there has been a steady relationship between global mined copper production and global refined primary production. This study uses the long-term average of this ratio—97.8%—as an identity to forecast primary production.	

High Ambition Scenario

Global refined copper production will grow from just under 25 MMt in 2021 to 47.3 MMt in 2035 under the High Ambition Scenario, with a compound annual growth rate of 4.7%. In 2035, primary production, or the refining of mined copper, will account for just under 37 MMt of refined copper, while secondary production, or the refining of recycled copper, will make up nearly 10.4 MMt of refined copper supply.

Breakdown of global refined copper production: High Ambition Scenario



Source: ICSG, S&P Global

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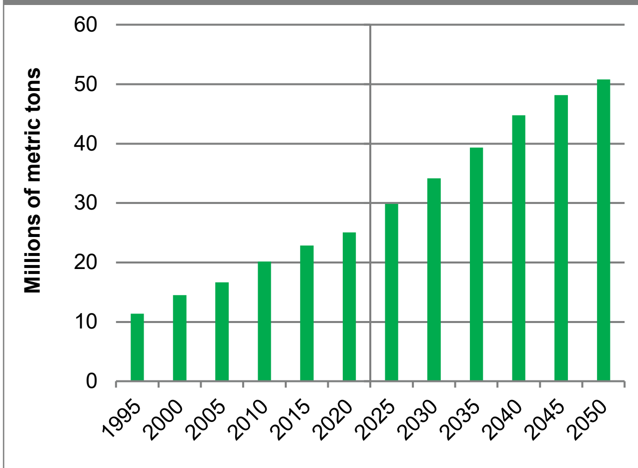
While primary production—which is driven by both mined output and capacity utilization—will grow at a compound annual growth rate of 4.2% between 2021 and 2035, mined capacity alone will only grow at a rate of 2.9% during the same period. Thus, the higher growth rate is made possible by increasing production from existing mines—that is, higher capacity utilization.

Global mined copper capacity: High Ambition Scenario



Note: Global mined copper capacity is assumed to be the same under both supply scenarios.
Source: ICSG, S&P Global

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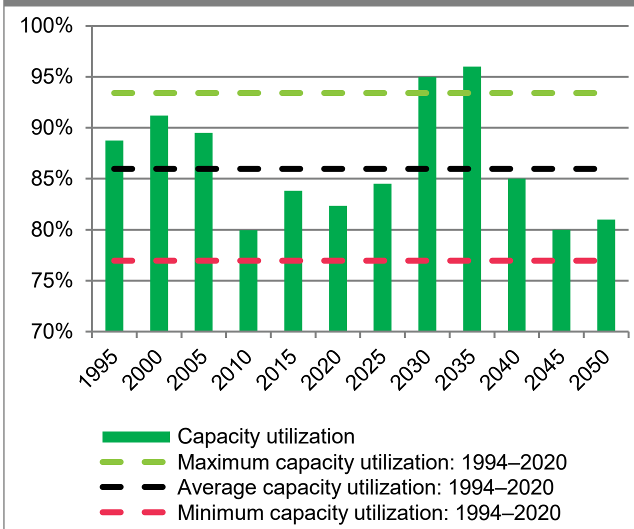
Global mined copper capacity utilization: High Ambition Scenario



Source: ICSG, S&P Global

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Low utilization rates are generally a byproduct of disruptions and unscheduled maintenance, rather than a conscious decision by producers to mine less material. Nonetheless, there is a relationship between prices and capacity utilization. A lower copper price may lead to the idling of high-cost operations, while higher prices incentivize “high grading”—that is focusing on the richest ore locations—and quickly resolving disruptions as much as possible. However, some of the environmental issues pose major concerns and require collaboration between mining companies and policymakers to provide resolutions. While the global capacity utilization rates assumed during the peak years of energy transition–related copper demand in the High Ambition Scenario exceed the peak global rates observed in the late 1990s, these assumed utilization rates on a country level are in line with the rate and duration of historical utilization in some key countries sustained above 95%.

The top five copper mining countries in 2021 will not change much by 2050, the only difference being Russia overtaking the United States as the fifth-largest copper mining country. This is mainly from the anticipated opening of the Ak-Sug and Malmyzhskoye mines, which will add 120,000 and 250,000 metric tons of annual capacity by 2026, respectively, according to the International Copper Study Group (ICSG). It is not possible at this point to assess the longer-term impact of Russia’s war in Ukraine on Russia’s position as producer and exporter of minerals and other commodities. It is important to note that the Oyu Tolgoi mine is Mongolia is slated to be one of the biggest mine expansions over the next several years, although it will not push Mongolia into the top five copper mining countries over the forecast horizon.

Top copper mining countries: High Ambition Scenario
(thousands of metric tons)

	2021		2035		2050	
Country	**Metric tons**	**Share**	**Metric tons**	**Share**	**Metric tons**	**Share**
Chile	5,616	26.3%	9,284	24.6%	10,417	25.3%
Peru	2,385	11.2%	4,888	12.9%	6,151	14.9%
China	1,890	8.9%	3,427	9.1%	3,195	7.8%
Congo, Democratic Republic of the	1,650	7.7%	3,128	8.3%	3,172	7.7%
United States	1,221	5.7%	1,903	5.0%	1,606	3.9%
Russia	895	4.2%	1,967	5.2%	2,099	5.1%
Rest of world	7,678	36.0%	13,167	34.9%	14,516	35.3%
World	**21,333**		**37,763**		**41,156**	

Note: Top five countries for each year shaded in light gray.
Source: ICSG, S&P Global

Meanwhile, secondary production growth will accelerate over the medium-long term as recycling rates increase. By the time of peak energy transition copper demand in 2035, secondary production from traditional copper end markets will double from the 2021 level, reaching over 8.3 MMt or 22.6% of primary production levels, slightly above the all-time high of 22.0% of primary production recorded in 2013. This increase will largely be driven by the high prices created by the large projected deficits. After 2038, growth of secondary production from traditional copper end markets will slow. This decline occurs because a better-supplied market in the 2040s will drive copper prices lower, reducing recycling incentives.

However, incremental secondary production of copper from energy transition end markets will grow between 2035 and 2050. During this period, copper used during the strong rise in energy transition copper demand from items such as electric cars will enter the physical scrap market, opening up opportunities for recycling. The annual incremental amount of secondary production from energy transition end markets will reach nearly 2.1 MMt in 2035 and almost 4.8 MMt in 2050.

Overall secondary production as a percentage of total refined production will increase from 16.4% in 2021 to 22.0% in 2035. The increase in recycling from energy transition end markets will offset the decline in recycling rates for copper used in nonenergy transition end markets over the following 11 years, with total secondary production as a percentage of total refined copper production peaking at 26.0% in 2046. Thereafter, total secondary production as a percentage of refined production will decline slightly.

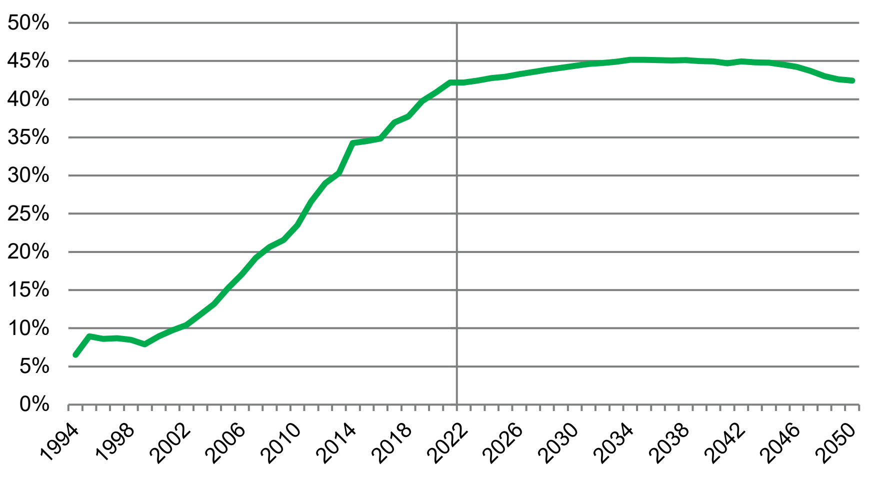
Top copper refining countries: High Ambition Scenario
(thousands of metric tons)

	2021		2035		2050	
Country	**Metric tons**	**Share**	**Metric tons**	**Share**	**Metric tons**	**Share**
China	10,536	42.2%	21,377	45.2%	22,811	42.4%
Chile	2,231	8.9%	3,466	7.3%	3,855	7.2%
Japan	1,518	6.1%	2,388	5.0%	2,396	4.5%
Congo, Democratic Republic of the	1,318	5.3%	2,172	4.6%	2,366	4.4%
United States	1,019	4.1%	1,791	3.8%	2,262	4.2%
Rest of world	8,359	33.5%	14,551	30.7%	20,071	37.3%
World	**24,980**		**47,323**		**53,760**	

Note: Top five countries for each year shaded in light gray.
Source: ICSG, S&P Global

Similar to the top copper mining countries, the makeup of the top producing countries of refined copper will not significantly change from 2021 to 2050. In fact, the top five producing countries of refined copper will be the same in 2050 as it was in 2021.

Chinese refined copper production as a percentage of global total: High Ambition Scenario

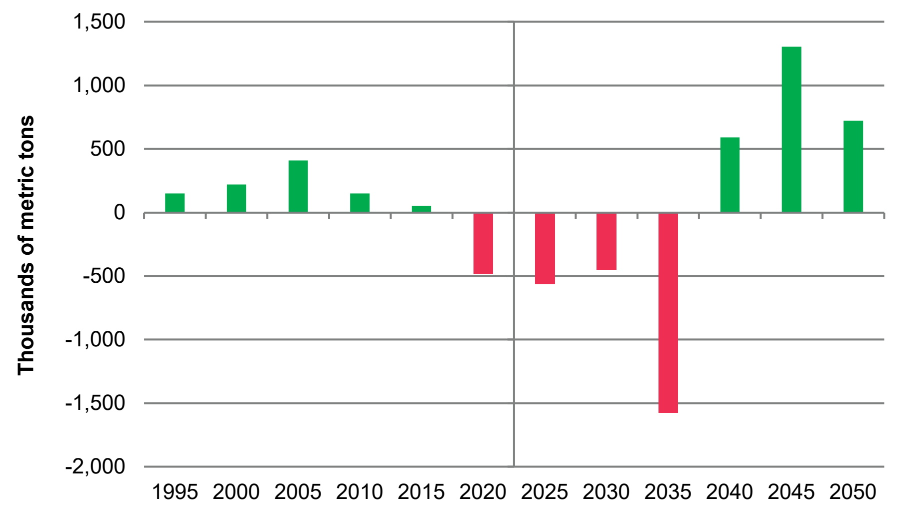


Source: ICSG, S&P Global

Chinese total refined copper production as a share of the global total has increased dramatically since 2000, growing from 8.9% in 1995 to 42.2% in 2021. Even though Chinese total refined production will continue to grow, its share of world production is projected to peak at 45.2% in 2035 and subsequently fall to 42.2% by 2050.

What are the implications on market balance under the High Ambition Scenario?

Global copper market balance: High Ambition Scenario



Source: ICSG, S&P Global © 2022 S&P Global

In the immediate near term, a recovery in mine production from pandemic-induced disruptions is expected to push the copper market into a brief and modest surplus. After 2024, however, the market is projected to shift back into shortfall, driven by an increase in energy transition demand. Strong continuing energy transition demand is expected to keep the market in shortfall through most of the 2030s. Recycling rates do increase during this period, but the corresponding growth in secondary production is not enough to offset strong consumption growth.

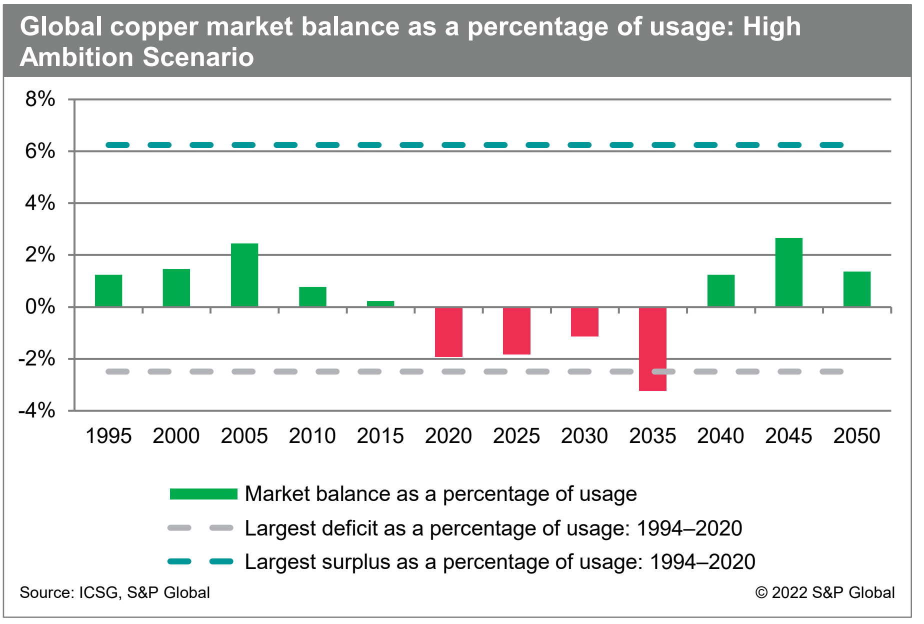
The annual shortfall in the High Ambition Scenario will exceed 1 MMt on five occasions between 2025 and 2040. The largest shortfall—projected at nearly 1.6 MMt—will occur in 2035, coinciding with peak energy transition demand. Should the pace of the energy transition be slower, this peak will be later.

Global copper supply and demand: High Ambition Scenario
(millions of metric tons)

	2020	2025	2030	2035	2040	2045	2050
Supply							
Primary production	20.6	24.7	31.7	36.9	37.2	37.7	40.2
Secondary production	3.9	5.4	7.7	10.4	11.2	12.7	13.5
Total refined production	**24.5**	**30.1**	**39.5**	**47.3**	**48.4**	**50.4**	**53.8**
Demand							
Energy transtion usage	6.6	9.1	14.4	20.5	16.2	14.8	16.0
Nonenergy transition usage	18.4	21.6	25.6	28.4	31.6	34.3	37.1
Total refined consumption	**25.0**	**30.6**	**39.9**	**48.9**	**47.8**	**49.1**	**53.0**
Market balance	**(0.5)**	**(0.6)**	**(0.5)**	**(1.6)**	**0.6**	**1.3**	**0.7**

Source: S&P Global © 2022 S&P Global

Beginning around 2038 in the High Ambition Scenario, a surplus will emerge in the market. This is due to the combination of the drawdown in energy transition demand and an increase in secondary production, particularly from energy transition end markets. The largest surplus is projected in 2045 when refined production will exceed consumption by approximately 1.3 MMt.



When considered at the margin and expressed as a percentage of total usage, the shortfall in 2035 is expected to be 3.2%. For reference, the largest shortfall as a percentage of use in the past 25 years was 2.5%, recorded in 2014.[28] Similarly, the 1.3 MMt surplus projected in 2045 is expected to be roughly 2.7% of global usage, similar in scale to the surplus recorded in 2005, which was 2.5% of total global copper use, but far lower than the surplus in 1998, which was 6.2% of global copper usage. This surplus is largely driven by two factors: the drawdown in energy transition demand after 2035 and the ramp-up in recycling from energy transition end markets. If the pace of the energy transition is slower than what is highlighted in the High Ambition Scenario, energy transition copper demand will peak later than 2035 and incremental recycling from energy transition end markets will impact the market later. Both events would substantially reduce the surplus projected in the 2040s and perhaps leave the market in either balance or shortfall.

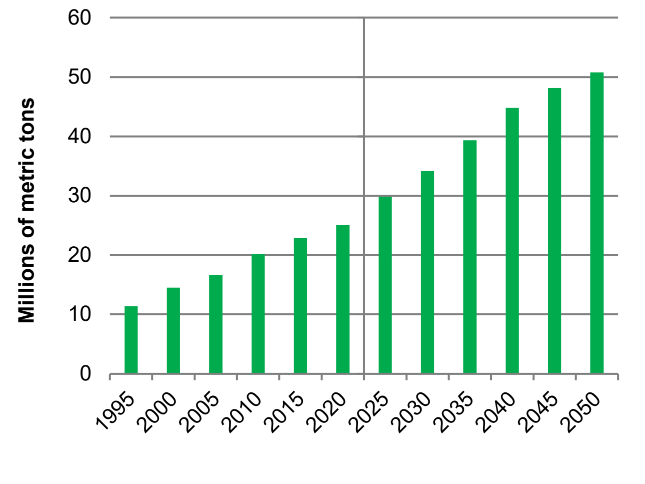
The chronic gap under the High Ambition Scenario between global supply and demand projected to begin in 2025 and lasting through most of the 2030s will have serious consequences for several markets. The gap results despite aggressive, yet not unprecedented at the country level, capacity utilization rates and all-time high recycling rates catalyzed by strong price signals and incentivizing policy initiatives. If these levels of utilization and recycling cannot be met, the supply gap would be even larger.

Rocky Road Scenario

Recognizing the extreme risk associated with the High Ambition Scenario, the Rocky Road Scenario assumes that both capacity utilization and recycling rates will be flat through 2050, continuing at their average levels from 2012 to 2021 (84.1% and 17.0% of total refined production, respectively).

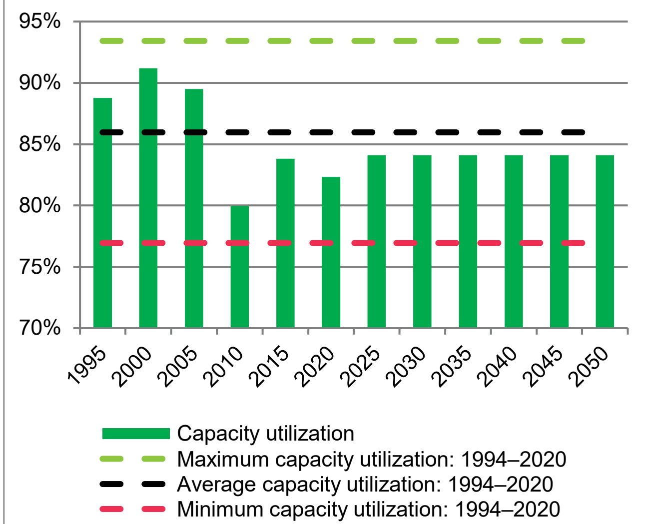
28. According to the ICSG.

Global mined copper capacity: Rocky Road Scenario



Note: Global mined copper capacity is assumed to be the same under both supply scenarios.
Source: ICSG, S&P Global

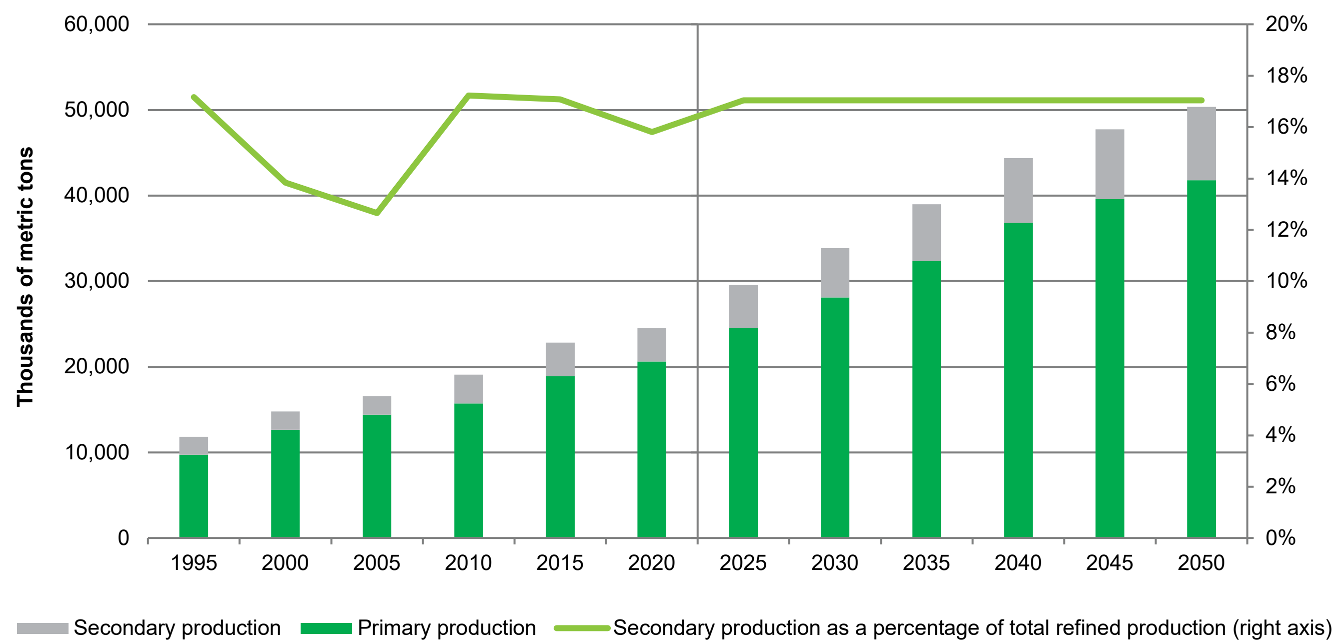
Global mined copper capacity utilization: Rocky Road Scenario



Source: ICSG, S&P Global

In this scenario, global total refined production is expected to reach 39 MMt in 2035 with a compound annual growth rate of 3.2%. In 2035, primary production, or the refining of mined copper, will account for 32.4 MMt of refined copper, while secondary production, or the refining of recycled copper, will make up 6.6 MMt of refined copper supply.

Breakdown of global refined copper production: Rocky Road Scenario



Source: ICSG, S&P Global

As is the case in the High Ambition Scenario, the only change in the top five copper mining countries between 2021 and 2050 will be Russia overtaking the United States as the fifth-largest copper mining country.

Top copper mining countries: Rocky Road Scenario
(thousands of metric tons)

	2021		2035		2050	
Country	**Metric tons**	**Share**	**Metric tons**	**Share**	**Metric tons**	**Share**
Chile	5,616	26.3%	8,819	26.7%	11,246	25.3%
Peru	2,385	11.2%	4,549	13.8%	6,431	14.9%
China	1,890	8.9%	2,742	8.3%	3,334	7.8%
Congo, Democratic Republic of the	1,650	7.7%	2,691	8.1%	3,118	7.7%
United States	1,221	5.7%	1,546	4.7%	1,631	3.9%
Russia	895	4.2%	1,865	5.6%	2,301	5.1%
Rest of world	7,678	36.0%	10,871	32.9%	14,670	35.3%
World	**21,333**		**33,082**		**42,731**	

Note: Top five countries for each year shaded in light gray.
Source: ICSG, S&P Global

Meanwhile, global secondary production will grow from just under 4.1 MMt in 2021 to over 6.6 MMt in 2035 and nearly 8.6 MMt in 2050 in the Rocky Road Scenario. Throughout this entire period, secondary production will be 17.0% of total refined copper production, which, again, was the global average between 2012 and 2021. Overall, global secondary production is projected to grow at a compound annual growth rate of 2.6% between 2021 and 2050 in this scenario.

Like the top copper mining countries, the makeup of the top producing countries of refined copper will not materially change from 2021 to 2050. Similarly, Russia will overtake the United States as the fifth-largest copper refining country under the Rocky Road Scenario.

Top copper refining countries: Rocky Road Scenario
(thousands of metric tons)

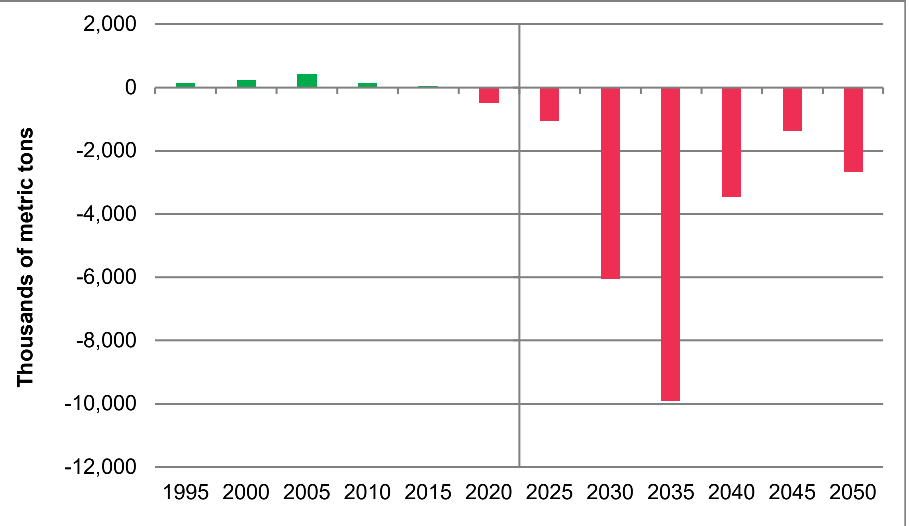
	2021		2035		2050	
Country	**Metric tons**	**Share**	**Metric tons**	**Share**	**Metric tons**	**Share**
China	10,536	42.2%	17,738	45.5%	21,593	42.9%
Chile	2,231	8.9%	3,036	7.8%	4,002	7.9%
Japan	1,518	6.1%	1,974	5.1%	2,300	4.6%
Congo, Democratic Republic of the	1,318	5.3%	1,902	4.9%	2,457	4.9%
United States	1,019	4.1%	1,385	3.6%	1,712	3.4%
Russia	933	3.7%	1,341	3.4%	1,772	3.5%
Rest of world	7,426	29.7%	11,621	29.8%	16,536	32.8%
World	**24,980**		**38,997**		**50,372**	

Note: Top five countries for each year shaded in light gray.
Source: ICSG, S&P Global

What are the implications for market balance in the Rocky Road Scenario?

The shortfall between demand ambitions and supply dramatically increases under the Rocky Road Scenario, reaching 9.9 MMt in 2035. Because there would be no energy transition recycling ramp-up in the 2040s due to the constant recycling rate under this scenario, the copper market would continue to be in shortfall through 2050 and beyond, with demand outpacing supply or refined copper by 2.7 MMt in 2050.

Global copper market balance: Rocky Road Scenario

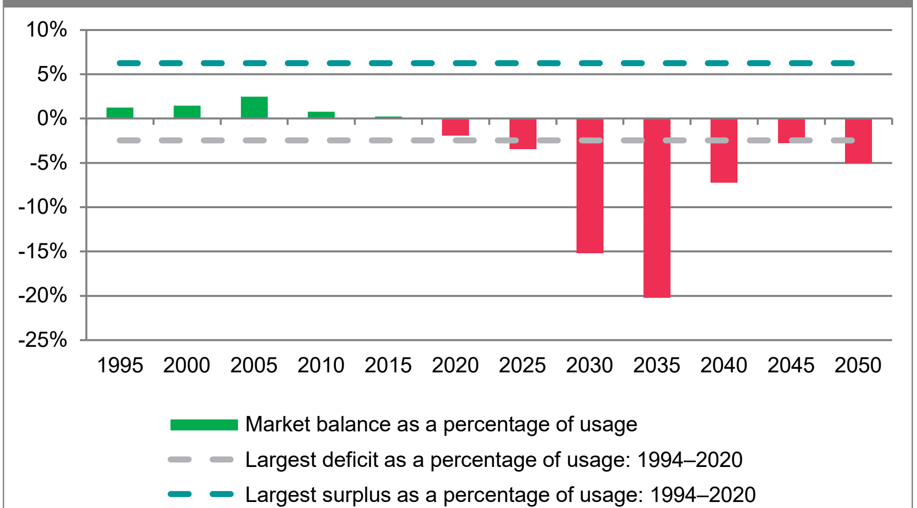


Source: ICSG, S&P Global © 2022 S&P Global

To put this in a historical context, these shortfalls as a percentage of global demand are unprecedented. With both primary and secondary refined production lower than in the High Ambition Scenario because of lower capacity utilization and recycling rates, most years in the outlook under the Rocky Road Scenario have demand outstripping supply by record levels.

The largest shortfall as a percentage of refined copper demand between 1994 and 2020 was 2.5%. The Rocky Road Scenario projects much larger shortfalls during the 2022–50 outlook, including a shortfall of more than 20% in 2035 alone. As discussed later, these chronic shortfalls would be wildly unprecedented within the copper market.

Global copper market balance as a percentage of usage: Rocky Road Scenario



Source: ICSG, S&P Global © 2022 S&P Global

Global copper supply and demand: Rocky Road Scenario
(millions of metric tons)

	2020	2025	2030	2035	2040	2045	2050
Supply							
Primary production	20.6	24.5	28.1	32.4	36.8	39.6	41.8
Secondary production	3.9	5.0	5.8	6.6	7.6	8.1	8.6
Total refined production	**24.5**	**29.6**	**33.9**	**39.0**	**44.4**	**47.7**	**50.4**
Demand							
Energy transition usage	6.6	9.1	14.4	20.5	16.2	14.8	16.0
Nonenergy transition usage	18.4	21.6	25.6	28.4	31.6	34.3	37.1
Total refined consumption	**25.0**	**30.6**	**39.9**	**48.9**	**47.8**	**49.1**	**53.0**
Market balance	**(0.5)**	**(1.0)**	**(6.1)**	**(9.9)**	**(3.5)**	**(1.4)**	**(2.7)**

Source: S&P Global

The mismatch between supply and demand ambitions in the Rocky Road Scenario is simply too large and long-lasting to occur. The chronic supply shortfall projected from the mid-2020s through the entire forecast period in the Rocky Road Scenario is untenable and would lead to both supply and demand-side reactions, likely including increased recycling and capacity utilization rates, as well as slower deployment of copper-intensive goods and technologies.

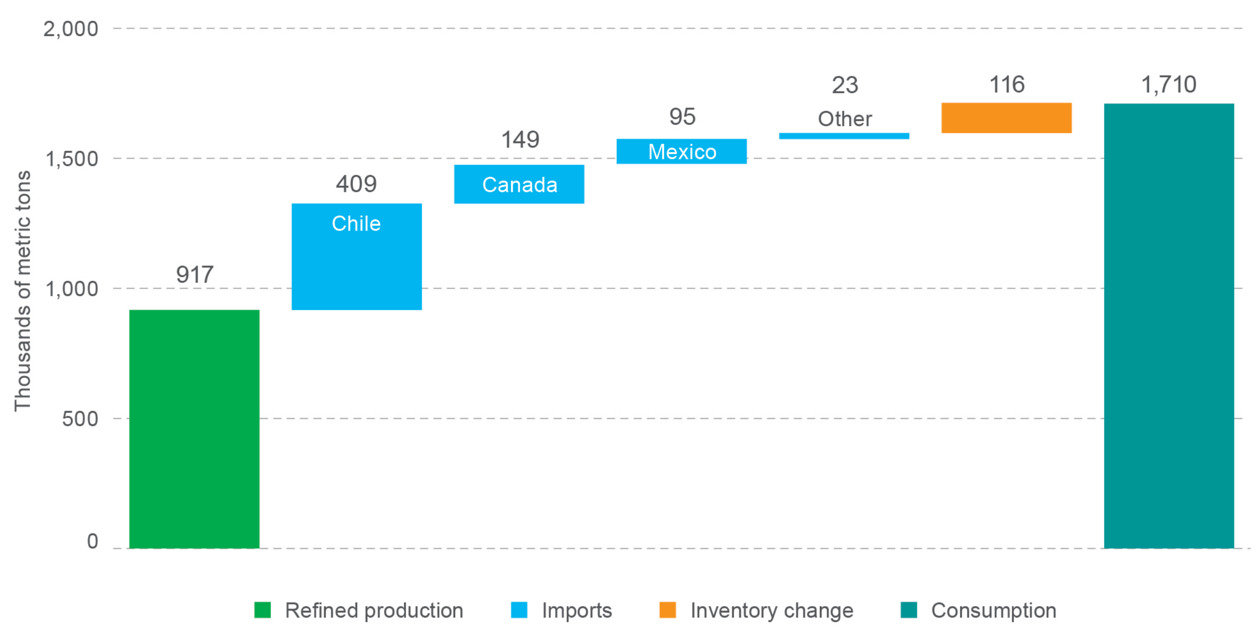
While the supply gap projected in the High Ambition Scenario is neither as long-lasting nor nearly as deep as what is estimated in the Rocky Road Scenario, it is still unprecedented and untenable for the global refined copper market. This would have several adverse effects on the users of copper, the energy transition and climate ambitions, and on businesses and consumers throughout the global economy.

Chapter 6. Impact for the United States

While copper has historically been an internationally traded commodity, for most of the 20th century, the United States was largely self-sufficient. Even as late as 1995, domestic refined production represented 90% of its copper needs, thus importing only 10%. But dependence on global markets has grown rapidly in this century even as domestic consumption has declined. Today, US domestic production amounts to only half of its copper requirements, a dependence that will grow substantially in the years ahead despite increased capacity utilization and stepped-up recycling. By 2035, the United States will be importing between 57% and 67% of its copper needs.

From where will needed supply come? In 2020, Chile accounted for 60.5% of US refined copper imports, while Canada and Mexico represented 22.1% and 14.1% of US imports, respectively. These percentages are likely to fluctuate over time.

US refined copper production, consumption, and imports: 2020



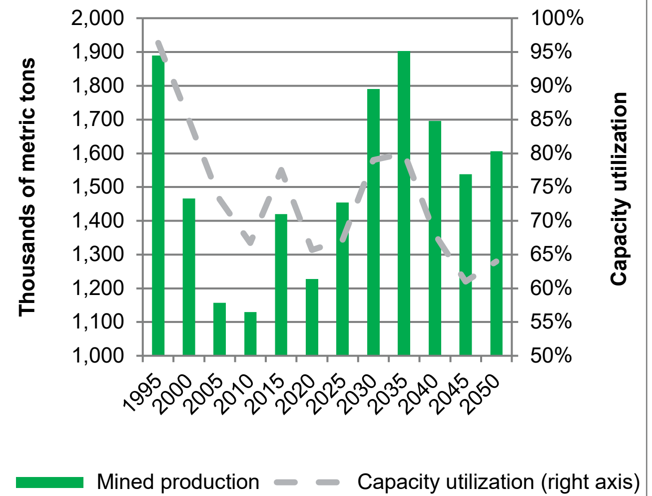
Source: International Copper Study Group (ICSG)

The United States will be even more dependent on imports over the next 15 years. Data from the ICSG shows the US shortfall as a percentage of usage was nearly 44% in 2020, a dependency that is expected to rise to the already noted 57% in 2035 in the High Ambition Scenario and 67% in 2035 in the Rocky Road Scenario. This means that during the years of peak energy transition copper demand, the United States will need to import well more than half of the refined copper it uses.

While the sustained shortfall can be largely attributed to the reduction in mined and refined production, usage of refined copper has also fallen in the United States since 2000. Production and usage have their own dynamics that have driven this pattern, such as, on the production side, the increasingly complex regulatory and permitting environment for mining and, on the demand side, offshoring to take advantage of lower production costs of downstream manufacturing.

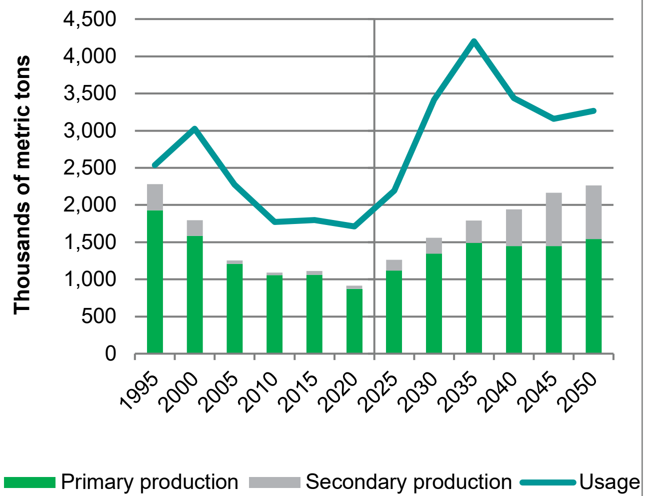
Indeed, there has been a degree of circularity in the deterioration of the US industry. The slow decline in mine production was accompanied by a concurrent reduction in smelting and refining capacity, which in turn caused recyclers to export scrap rather than reprocess and recover metal in the United States. The net effect was a reduction in domestic refined copper supply, creating an additional challenge for downstream electric equipment manufacturers already facing increased competition from lower-cost foreign producers. The loss in domestic US wire and cable demand, however, provided little incentive to invest in even maintaining existing copper smelting and refinery capacity and so on.

US mined copper production and capacity utilization: High Ambition Scenario



Source: ICSG, S&P Global © 2022 S&P Global

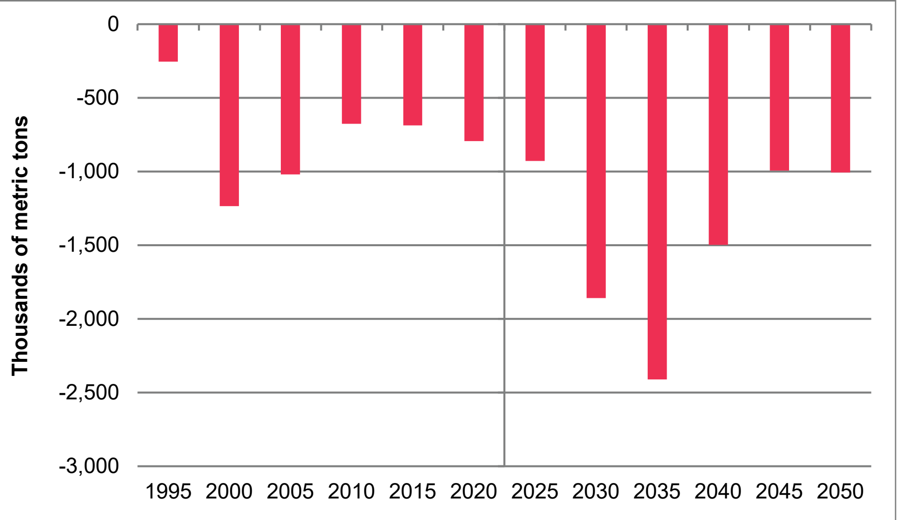
US refined copper usage and production: High Ambition Scenario



Source: ICSG, S&P Global © 2022 S&P Global

The US market balance will fall further into shortfall, peaking at a deficit of just more than 2.4 MMt in 2035 in the High Ambition Scenario, which represents over half of US refined copper use during peak demand from energy transition technologies.

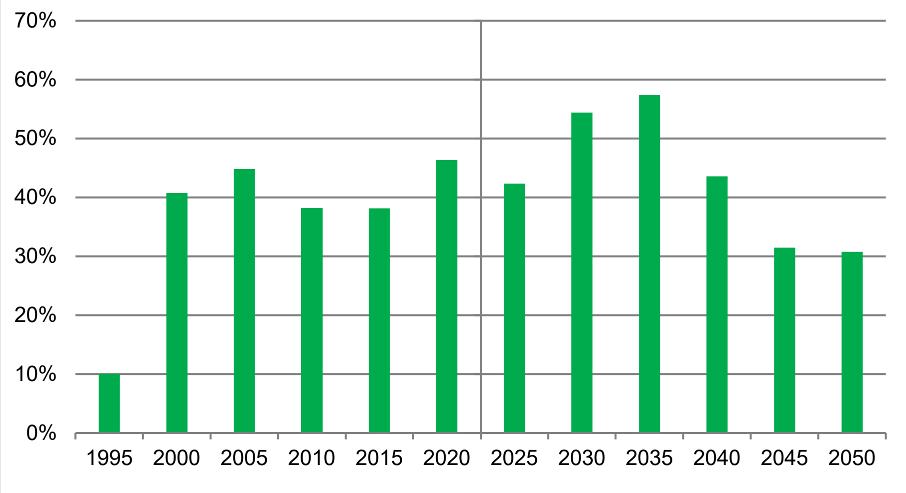
US refined copper market balance: High Ambition Scenario



Source: ICSG, S&P Global © 2022 S&P Global

These shortfalls mean that the United States will continue to be dependent on imports to balance the domestic market throughout the forecast in the High Ambition Scenario.

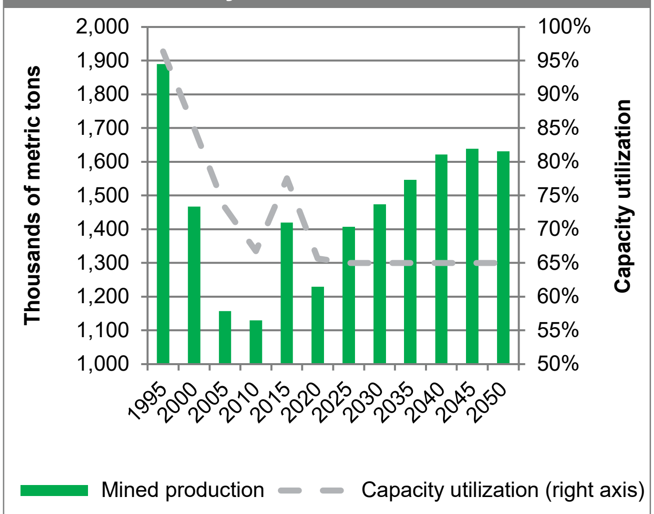
Percentage of US copper demand reliant on imports: High Ambition Scenario



Source: ICSG, S&P Global © 2022 S&P Global

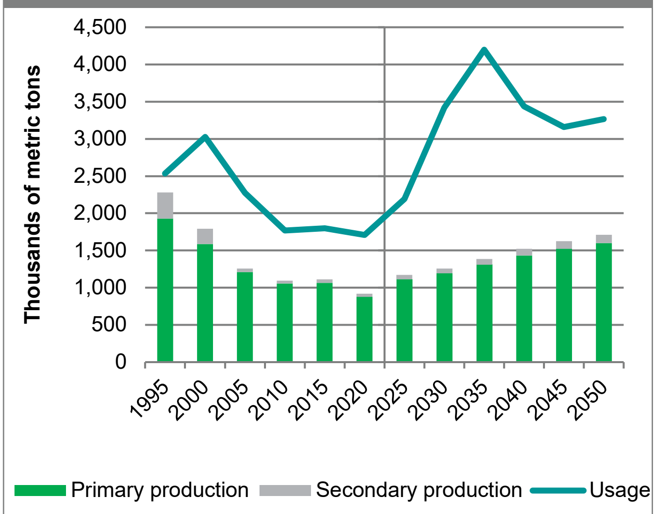
As is the case in the High Ambition Scenario, the United States will have a chronic gap between demand and supply for years to come under the Rocky Road Scenario, albeit a larger one. Because the influx of energy transition–related recycling is much lower throughout the entire outlook in this scenario, secondary production growth will be much lower than that of the High Ambition Scenario.

US mined copper production and capacity utilization: Rocky Road Scenario



Source: ICSG, S&P Global © 2022 S&P Global

US refined copper usage and production: Rocky Road Scenario

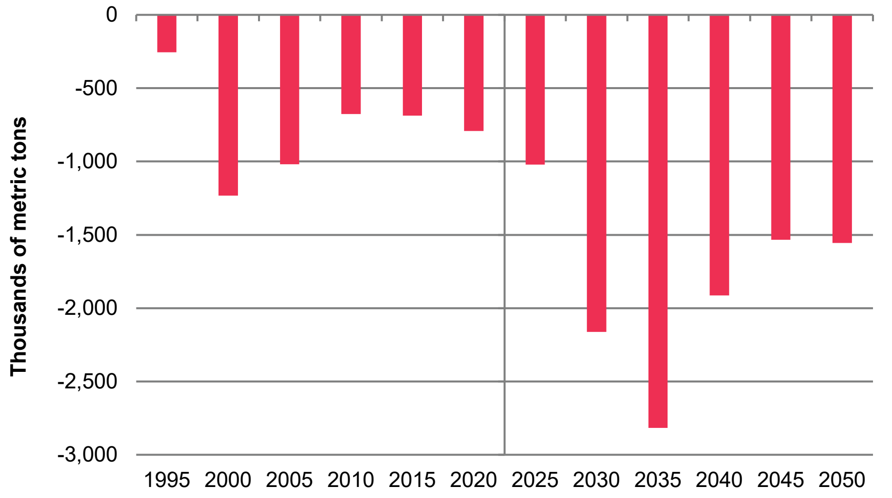


Source: ICSG, S&P Global © 2022 S&P Global

In the Rocky Road Scenario, the shortfall in the United States will grow even larger, reaching 2.8 MMt in 2035 before slipping back to 1.5 MMt in 2050.

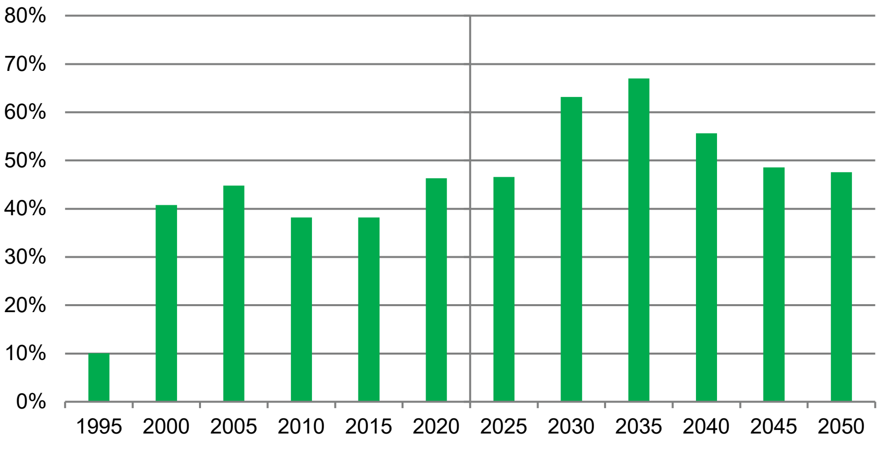
This deeper shortfall means that the United States would become even more dependent on external sources of supply, relying on imports for as much as two-thirds of total demand in 2035 when energy transition–related use is strongest.

US refined copper market balance: Rocky Road Scenario



Source: ICSG, S&P Global

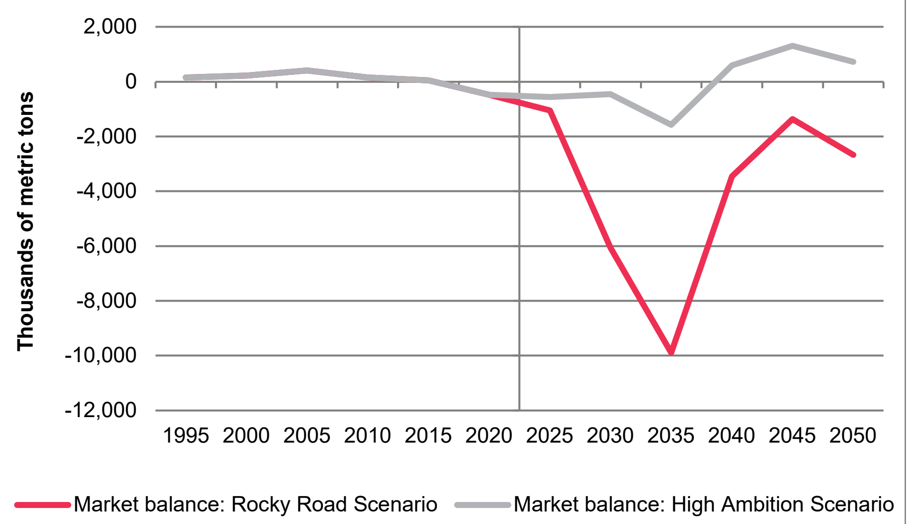
Percentage of US copper demand reliant on imports: Rocky Road Scenario



Source: ICSG, S&P Global

Chapter 7. Impact of shortfalls on markets

Global copper market balance



Source: ICSG, S&P Global

A supply gap of the size projected in the High Ambition Scenario, let alone the Rocky Road Scenario, would exert tremendous upward pressure on copper prices. Given copper's use in a range of end markets, these cost pressures would be transmitted throughout the supply chain, lifting prices for intermediate and finished goods such as EVs as well as consumer prices for durable goods. In addition to substantial price increases, a copper shortage would disrupt supply chains and thus make achieving climate change targets even more challenging. Under the Rocky Road Scenario, Net-Zero Emissions by 2050 would not be a possibility.

Supply forecasts by scenario
(thousands of metric tons)

	2020	2025	2030	2035	2040	2045	2050
High Ambition Scenario							
Mine capacity	25,059	29,837	34,157	39,337	44,777	48,144	50,810
Capacity utilization	82.3%	84.5%	95.0%	96.0%	85.0%	80.0%	81.0%
Mine production	20,634	25,212	32,449	37,763	38,061	38,515	41,156
Primary production	20,635	24,655	31,733	36,929	37,220	37,664	40,247
Secondary production	3,875	5,409	7,732	10,394	11,215	12,737	13,513
As a percentage of total refined production	15.8%	18.0%	19.6%	22.0%	23.2%	25.3%	25.1%
Total refined production	**24,509**	**30,064**	**39,464**	**47,323**	**48,434**	**50,402**	**53,760**
Rocky Road Scenario							
Mine capacity	25,059	29,837	34,157	39,337	44,777	48,144	50,810
Capacity utilization	82.3%	84.1%	84.1%	84.1%	84.1%	84.1%	84.1%
Mine production	20,634	25,093	28,726	33,082	37,658	40,489	42,731
Primary production	20,635	24,539	28,092	32,351	36,826	39,595	41,787
Secondary production	3,875	5,041	5,771	6,646	7,565	8,134	8,585
As a percentage of total refined production	15.8%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%
Total refined production	**24,509**	**29,580**	**33,863**	**38,997**	**44,391**	**47,729**	**50,372**

Source: S&P Global

This study quantifies the gap between the copper required to meet stated Net-Zero Emissions by 2050 policy ambitions and the amount of supply that can be delivered. Matters are made more complicated, as copper is an internationally traded commodity; but mining, processing, and consumption all take place within national borders. Altogether, it is unlikely that such a gap between supply and demand ambitions would exist for so long.

How could the gap be closed? What could be the path out of the gap?

- **What about a diminished demand because of a slower uptake by energy transition markets?** Because energy transition markets will drive much of the growth in overall copper demand through 2035, one consequence might be a slower energy transition if any of the major energy transition markets cannot grow as fast as projected. As a result, goals of Net-Zero Emissions by 2050, for example, could take longer to be attained. As the Copper requirements in the energy transition section notes earlier in this study, copper requirements in both the Inflections and Green Rules cases are only marginally lower than the copper required in the Net-Zero Emissions by 2050 case for the United States and the MTM case for the rest of the world.

- **What about reducing demand through efficiencies and technological change?** Another way part of the gap could be closed is by reducing the copper intensity in both energy transition and nonenergy transition technologies from technological and engineering advancements and efficiency gains from economies of scale. A gradual reduction in copper intensity has been occurring within technologies like onshore wind turbines and solar PV technologies. This study assumes that the rate of efficiency gains in copper intensity will continue through the forecast period. Failing to maintain the efficiency gains would actually widen the gap. The obvious answer to the gap is that a major technological or engineering breakthrough dramatically altering copper intensity and its rapid diffusion. But no such technology appears to exist today at scale.

- **What about material substitution?** There is generally an increase in material substitution from copper to aluminum when the price of copper exceeds the price of aluminum by a factor of 3.5 to 4.0. While some substitution to aluminum could happen under this scenario, it would not be nearly enough to close the gap. Research commissioned by the International Copper Association estimates that material substitution will represent only roughly 1.3% of annual copper demand in the next five years. Copper's conductivity; energy efficiency; and high corrosion, friction, and fire resistance limit the amount of copper that reasonably can be substituted. Also, the production process for aluminum is very energy intensive. While estimating the aluminum required for the energy transition is out of the scope of this study, it is likely that the energy transition would also put a strain on the aluminum market. This is especially true for EVs, which use more aluminum to reduce weight and thus improve battery performance. As a result, it is not obvious that the price of copper would necessarily exceed the price of aluminum by a factor of 3.5 to 4.0 on a continuing basis. In short, material substitution is likely to prove a limited solution to closing the supply gap, at best.

- **What about increasing supply with technological advances?** Without increasing capacity, mined copper production can increase if there were technological improvements that would increase yields and capacity utilization. Over the past 50 years, productivity growth in the mining industry has helped offset the decline in ore grades, such that production has increased despite the declining quality of the resource base. Rapidly growing markets and sustained high prices incentivize new production technologies and methods; but development, adoption, and diffusion are part of a multiyear process in mining.

- **What about more mined capacity coming online?** Another way to augment supply is by increasing mined capacity through both brownfield expansion of existing mines and greenfield investment in new mines and facilities. While several brownfield and greenfield opportunities have been identified by the mining industry, both public policy and public opinion act as headwinds to developing these opportunities. This is evident in the decline in US mined copper production from almost 2 MMt in 1997 to just over 1.2 MMt in 2021. While increasing mining capacity would certainly help close the supply gap, much would be required to lower the 16-year average that the IEA has estimated that it currently takes to move mining projects from discovery to production. If copper deposits discovered today cannot be made available for production until after 2035, then Net-Zero Emissions by 2050 will not be achieved.

In sum, the mismatch anticipated in this study between demand and supply will put pressure on the goal of Net-Zero Emissions by 2050 and will likely slow the pace of energy transition.

The High Ambition Scenario assumes an aggressive use of existing resources between capacity utilization rates that are strong, yet within the outer edge of historical bounds, and recycling rates that are beyond the historical range. Despite these aggressive assumptions, a chronic shortfall for a period of almost 15 years is projected. If assumptions for the future are based on trends since 2012, as they are in the Rocky Road Scenario, wherein that capacity utilization and recycling rates continue at current rates, the supply gap becomes substantially more dramatic.

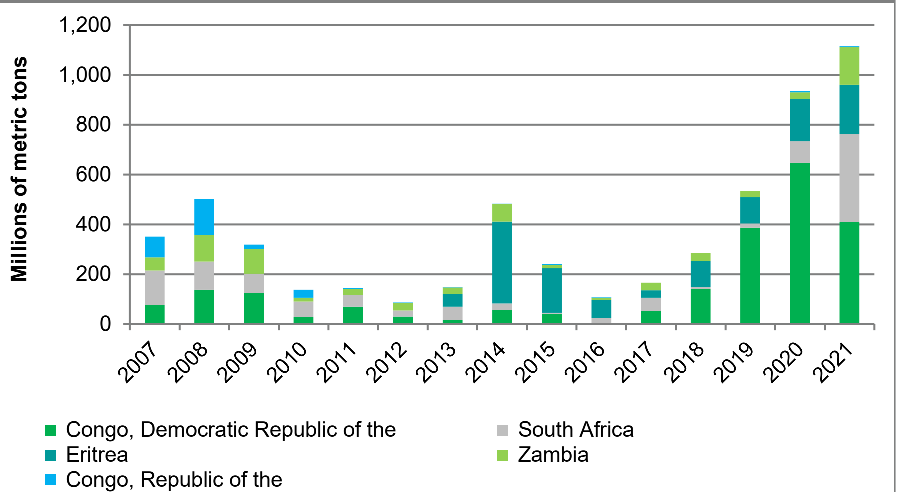
The objective of this study is to size the gap between policy ambitions and the level of production that can be delivered in the years ahead. It is not intended to recommend or predict which possible solutions or combination of solutions should or can fill the supply gap.

Adding to the complexity of what is ahead, there are a myriad of operational risks relevant to the countries that currently mine and refine copper and thus to the scale of the gap. The next section of this report will focus on these operational risks, on managing them, and what they could mean for the future of copper supply.

Chapter 8. Operational challenges

A range of risks and complications will have a major impact on the degree to which the global mining industry will be able to ramp up supplies in response to the "New Era of Copper Demand." How they play out will do much to determine which scenario ends up approximating reality. The shortfall will worsen if mine developments and utilization rates are suppressed by disruptions from labor strikes, protests, environmental activism, domestic political rivalries, governmental shifts, and contractual disputes and renegotiations that delay projects and investment. Brownfield and greenfield development of new projects turn on the complex interaction of permitting and policy, contracts and politics, and businesses and civil society that comprise the social license to operate. The upward pressure on global copper prices may reinforce governments' propensity to capture revenues and value from, and control of, this revenue-generating sector and its markets.

Chinese imports of copper ores and concentrates from its five largest Sub-Saharan African partners



Source: S&P Global

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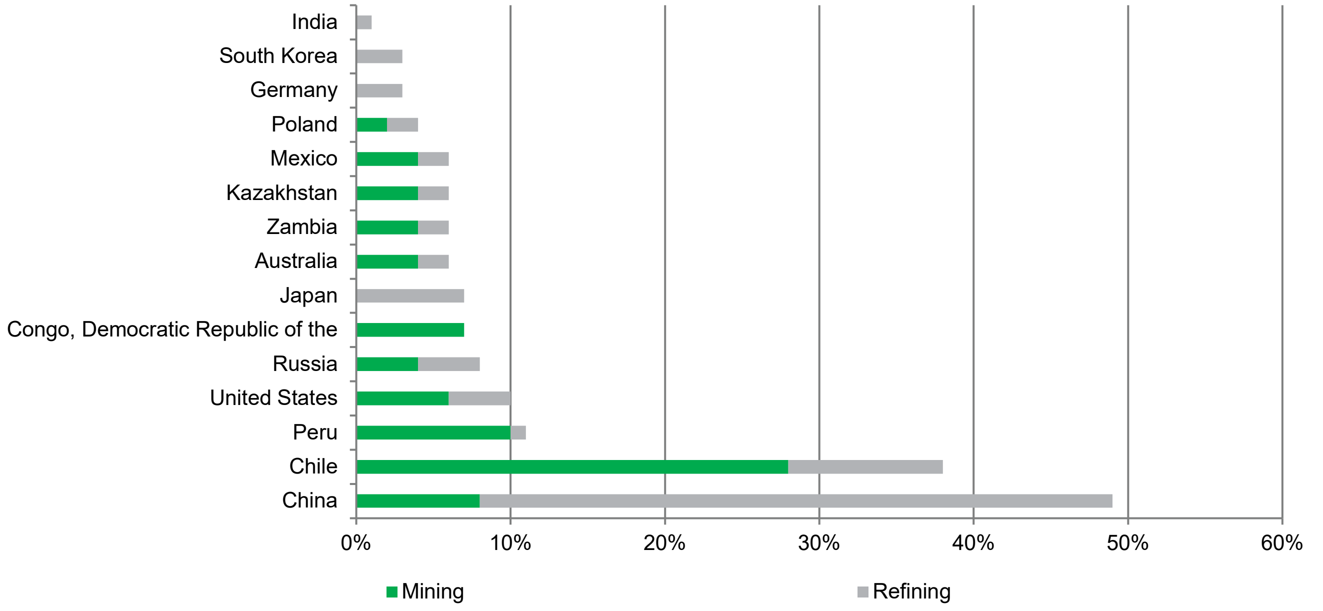
These risks are almost certain to be complicated by shifting geopolitics. *Chapter 6: Impact for the United States* noted that even in the High Ambition scenario during the years of highest energy transition–related copper demand, the United States will need to import more than half of the refined copper it uses. Its refined copper shortfall relative to usage is projected to rise to 57% by 2035, compared with 44% today (and just 10% in 1995). Under the Rocky Road scenario, the United States will have to import 67% of its copper by 2035. Some of this this will likely come from China, which already accounts for over 35% of global refined production. China's demand and production have soared over the past 25 years with the country's rapid industrialization, especially after China's ascension to the World Trade Organization in 2002. Rapid growth on the production side of the market was the result of a policy of targeted investments in smelting and refinery capacity that was designed to support growth in the country's electrical grid, high-speed rail network, and building stock. Indeed, over the past 20 years, China's smelters have displaced the so-called Japanese smelter pool to be the dominant player in the market for mined concentrates. Moreover, China has already established strong relationships with major copper mining countries in Sub-Saharan Africa, and more recently Latin America. These relationships are often led by state-owned enterprises (SOEs), whose long-term planning to secure important supply chains for China allows them to take on commercial risks that private firms, bound by demands to maximize shareholder value, cannot.

What is often now described as "great power competition" will increasingly emphasize supply chain resilience, including that for copper. The United States, the European Union, China, and the "Quad" (the United States, India, Japan, and Australia) have all linked supply chain resilience to core national interests. New geopolitics around the minerals for net zero may well emerge, which will echo the geopolitics that have long surrounded oil and natural gas. Even if copper is not officially designated a "critical mineral" by the US government, its overarching strategic importance is clear.

The set of national jurisdictions in which operational risks arise is diverse, but the key copper-sourcing countries will remain broadly the same over the projected period, even if their rankings change. Australia, for example, will be increasingly important in the global supply chain. Fifteen countries account for at least 1% each of global copper mining and/or refining—and together account for 80% of the global total.

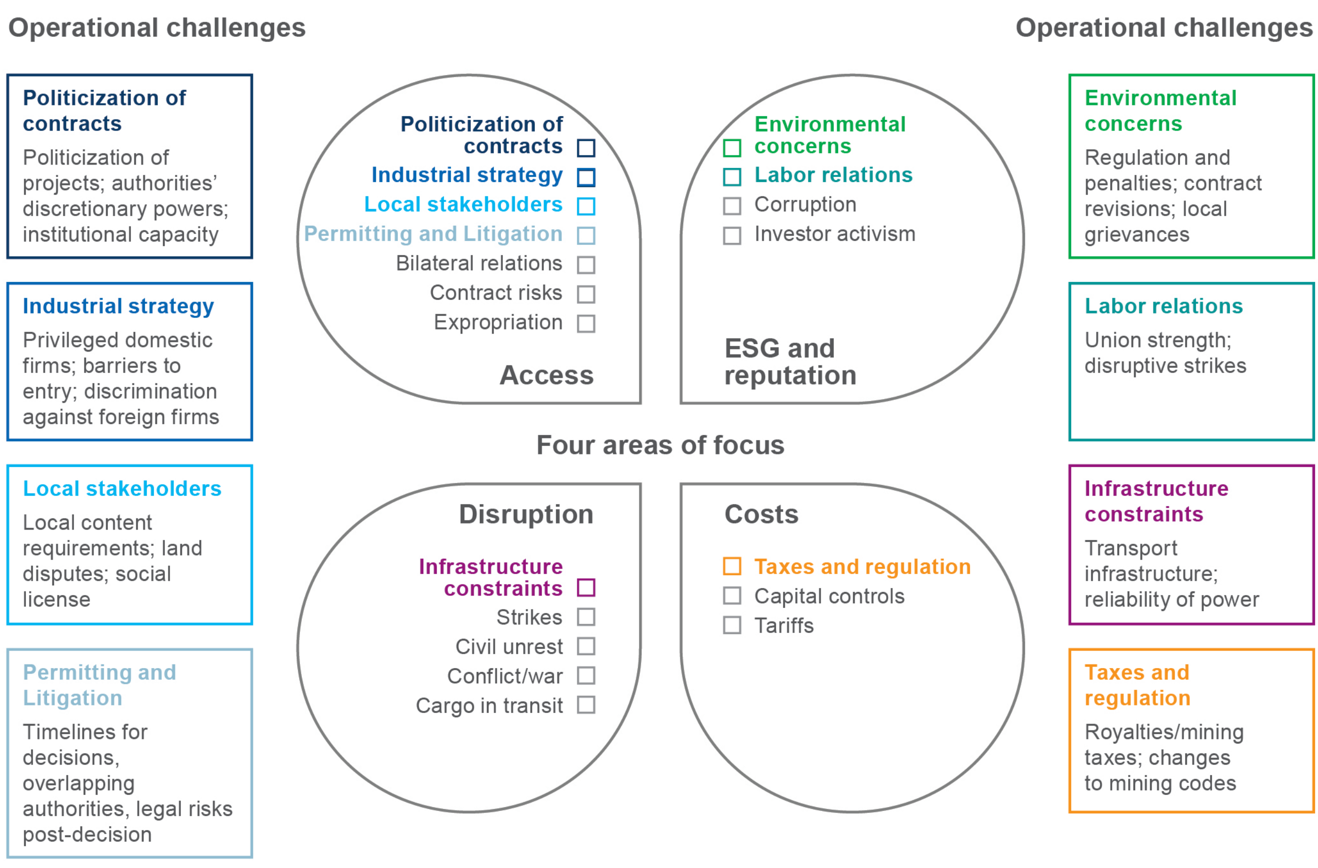
Countries with at least 1% global share of mined and/or refined copper, 2020



Note: These 15 countries together account for roughly four-fifths of global copper mining and refining (combined). Each country accounts for at least 1% of coppery mining and refining (combined).
Source: World Bureau of Metal Statistics

However, the relative stability of the positions of the sourcing countries may mask the operational issues and challenges in these countries for copper production. Eight operational challenges recur across geographies that can impede the additional output required by for the 2050 objectives.

Operational challenges of copper



Source: S&P Global Country Risk

Eight operational challenges

1. Infrastructure constraints

Deficient or poorly maintained roads, railroads, and ports create challenges to the effective and timely transport of copper ore to refineries and of products to export destinations in key copper sourcing countries in Latin America and Sub-Saharan Africa. For example, inadequate or unpaved roads in a mining corridor that may run through communities can slow cargo and leave it vulnerable to the frequent blockades by local protesters, or transport may be vulnerable in some countries to attacks by insurgents. Chronic power shortages force projects to install and maintain dedicated generators and increase operating costs.

In most sourcing countries, there is no clear plan for the large investments needed in new roads, water treatment, and expanded power grids. According to Infralatam, Latin America's public investment in infrastructure has fallen in recent years to below 2% of GDP as of 2018 and fell slightly further in 2019 (the last year of data available).[29] Further investment will be key to develop the required infrastructure; but even with investment, execution will take time and, in

29. Infralatam is a joint initiative between the Inter-American Development Bank, the Development Bank of Latin America, and the United Nations Economic Commission for Latin America. http://infralatam.info/en/home/. Data accessed on 20 June 2022.

many instances, will be challenged by complex regulatory environments and conflicting local stakeholder agendas, and in some jurisdictions, by political instability.

2. Permitting and litigation

Particularly in developed markets with high levels of transparency and both political and civil society scrutiny of policy, timely and transparent **permitting** is a fundamental operational challenge to supplying copper for the energy transition. The complicated interaction of federal, state, and local laws; the wide range of authorities involved; and the range of competencies required from consultation with local communities to highway safety and hazardous waste management all add to the scale and complexity of permitting. The process can often take many years and hundreds of millions or even billions of dollars before the first shovel is turned. Similar factors shape **litigation** risks. The possibility of legal intervention during all stages of the permitting process is particularly acute in countries with a highly developed, multilevel, multijurisdiction judiciary, with multiple opportunities for delays and injunctions. (See Appendix A on permitting in the United States). These factors can also apply in sourcing countries and are compounded by political uncertainty and intervention.

In nearly every jurisdiction, a new mine seeking permission today would not be productive until the late 2030s. Expedited permitting processes could attract capital, speed up execution, and reduce uncertainty. The expansion of the gap that exists between planning and opening a facility is demonstrated by comparing a 1956 US Bureau of Mines report that warned that copper mines may take as many as "three to four years" to construct and deliver product—a process that would have included permitting along with everything else.[30] Today, the permitting process by itself can take well over three or four years. Expedited permitting itself, however, could encounter new litigation challenges. Growing environmental activism and issues of peoples affected by mining projects add to this risk both in mature and emerging economies.

3. Local stakeholders

Local content requirements for suppliers and labor are very likely to become stricter in copper-sourcing countries as those governments seek to capture value from their strategically important industries. As a global shortfall of copper puts upward pressure on prices, these governments' motivation will strengthen. Breaches of compliance requirements will incur harsher fines and increasingly trigger threats of contract renegotiation. Threats of contract renegotiation from national and regional authorities have become more frequent in several countries.

New requirements for early consultation with affected communities will add to project delays, legal challenges, and contract revisions—most clearly in the increasing number of countries that have ratified International Labor Organization's (ILO) Convention 169. ILO Convention 169 seeks to guarantee the rights of indigenous and tribal peoples and obliges ratifying governments to safeguard these peoples' use of their traditional lands and the natural resources associated with them.[31] New policies can extend consultation requirements prior to the development phase of

30. USGS, 2021.

31. International Labour Organization, "Indigenous and Tribal Peoples Convention, 1989 (No. 169)," https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100_INSTRUMENT_ID:312314:NO. It provides to "consult the peoples concerned…The peoples should have their right to decide their own priorities for…the lands they occupy." "Lands…The peoples should be consulted whenever consideration is being given to…transmit their rights outside their own community."

a mine site and allow license cancellation in indigenous land years after the project has begun. Additional elaboration for social license can also jeopardize the viability of new projects as a whole and can trigger additional regulatory strictures.

Social license in Latin America

The copper industry, like other extractive industries, is likely to face growing challenges in several jurisdictions for social license to operate. Companies will likely need to expand the nature and features of their economic and welfare contributions to peoples affected by their operations in order to secure support. Whereas historically a social license was obtained by employing local residents and developing local infrastructure, including schools and healthcare facilities, miners will increasingly be benchmarked against broader criteria.

Currently, these challenges are concentrated in Latin America, where hundreds of mining projects—mainly in Chile, Peru, and Mexico—are delayed or intensely opposed. The absence or insufficiency of what is described as "prior consultation" is often an important cause of project delays. (Of the 24 countries, 15 that have ratified ILO Convention 169 are in Latin America.) Some countries, including Chile and Mexico, also implement citizen consultations. However, none of these are binding, unless required by domestic law—as in Peru. Failure to follow what litigants describe as the appropriate consultation process or not respecting their results, even if nonbinding, is likely to trigger legal challenges or protests against the project, causing disruption and delay, sometimes even after obtaining environmental approval. With local communities and NGOs becoming increasingly alert to the instruments and mechanisms available, they are likely to demand stronger consultations for all projects where all residents, not only indigenous groups, have a say and work to make the outcome binding. Some NGOs that are opposed to development and mining in general may cite the need for "consultation" as a means to block new mines, expansions, or current operations.

Social license is an increasingly pervasive concept. It is also nebulous and difficult to quantify by nature, determined by subjective, localized opinions, beliefs, and intersecting agendas. Emerging regulation offers some solidity but is subject to changing political dynamics. This will inherently affect the pace and scale of investment.[1]

1. Chile's draft new constitution, presented on 4 July 2022, would extend the rights of indigenous peoples over their traditional lands – and would grant rights of protection to "nature" itself. It is due to be voted on in September 2022.

4. Environmental standards

Stricter requirements for environmental issues, especially over the use of water, waste management, lowering carbon emissions, and preventing deforestation, are very likely to become an international norm. Subnational authorities are likely to adapt these norms to the extent their national laws allow. Higher fines, when applied, are likely to add to reputational risk, while cases of severe environmental damage can lead to suspension or cancellation of projects. Legislation in some countries is broadening the environmental factors considered when evaluating a project and provides powers to preempt what are designated or projected as environmental threats. The European Union Emissions Trading System (EU ETS) and the forthcoming Carbon Border Adjustment Mechanism (CBAM), China's 14th FYP and longer-term goals around greener technologies, and renewed US commitment to the Paris Agreement will be the cornerstones of international policy as these countries "export" their standards and policies.

Adoption of innovative technology and engineering that reduce GHG emissions associated with mining could both help meet new regulatory thresholds and contribute to the industry's social license to operate among policymakers and some environmental groups—but can take up to a decade to implement. Investment in existing or new carbon emission–reducing technology could also affect investment in new mine capacity. Higher recycling rates in downstream industries would, indirectly, have similar effects on the overall emissions of the industry.

5. Taxes and regulation

Tighter environmental regulations will increase the tax bills for copper miners. Many jurisdictions are likely to apply general environmental taxes to all industries on items like carbon emissions, fuel use, and water pollution. Even if copper's crucial role in the energy transition becomes widely understood, an increase in global copper prices as demand outstrips supply would incentivize the call for higher taxation on the sector to increase government take—either via new royalties, windfall taxes, or changes in the taxation system—and to capture more value domestically from this sector. Initiatives may be opaque, specified under unpublished conventions and negotiated outside of the mining code.

In many jurisdictions prevailing fiscal realities will drive decision-making rather than global energy transition agendas; and rising prices will provide a reason to raise taxation to meet budgetary needs irrespective of the negative impact on operations and new investment.

6. Politicization of contracts

Discretionary authority and the politicization of contracts and permits will continue to generate operational uncertainty in several sourcing countries. While some countries have stable frameworks and predictable policy, in others mining policy can vary dramatically as governing parties change with elections. The allocation of opportunities varies by government, likely including contract renegotiations that aim to replace influential stakeholders allied to former governments. The risk of contract alteration, either unilaterally by the government or via referenda, will remain high—constituting what has been called, once capital is sunk, the "obsolescing bargain."[32] Referenda have increasingly been used to block mining projects. Incoming governments can reverse a previous government's policies, adding to uncertainty and delaying or discouraging investment. This points to a larger consideration: the political calendar in countries is often much shorter than the investment calendar for major mining projects. Yet stability in contracts and regulations is an essential foundation for higher production to support the 2050 goals.

Escalating regulatory, taxation, and corruption investigation pressures are likely to be used by some countries to compel mining companies to renegotiate. Governments will likely require greater commitments to and investment in domestic processing of industrially mined copper. Antiextractive protests and sometimes an activist judiciary will potentially force state governments to close some sites. Where politics is particularly adversarial and corruption

32. Raymond Vernon, Sovereignty at Bay: *The Multinational Spread of US Enterprises*, Basic Books, New York, 1971.

allegations and investigations tend to follow elections, both existing and new mining projects—owing to their scale and importance—will face delays and disruption if they get caught in the political crossfire and become targets in themselves.

7. Labor relations

Where mining accounts for a significant percentage of GDP, mining unions are likely to have significant leverage. Strikes normally last between a few days to several weeks and, in most cases, consist of work stoppages, roadblocks, and blockades to the premises, disrupting operations and, in some cases, damaging vehicles and machinery. Significant labor disputes at major mines, which disrupt operations, can have a global impact, which may not be buffered by stockpiles.

8. Industrial strategy

The widening appreciation of copper's strategic importance and its scale and visibility in some countries will lead to greater political engagement in mining for economic and development reasons. Groups in some countries are likely to go as far as demanding the nationalization of the sector; but this is less likely to materialize in countries that have a successful record of public-private partnerships in the sector or in less-developed countries where the state does not have the financial or technical capacity to participate in the sector. Rather, closer scrutiny of foreign private companies' or SOEs' operations is likely.

State-owned mining and processing companies in some countries will probably take a more prominent role in coming years, potentially via joint operations with private actors, or by maintaining and strengthening state-owned companies. Monopolies or oligopolies with strong links to the state pose an additional entry barrier for new operators in some jurisdictions. Changing industrial strategy by governments may increasingly force miners to partner with SOEs, including in problematic jurisdictions, which can significantly alter project economics.

Three disruptors

Operational risk is dynamic and will undoubtedly change over the coming decades. While there is great uncertainty around those changes, three critical global "disruptors" emerge that would significantly change operational risk—for the better or worse.

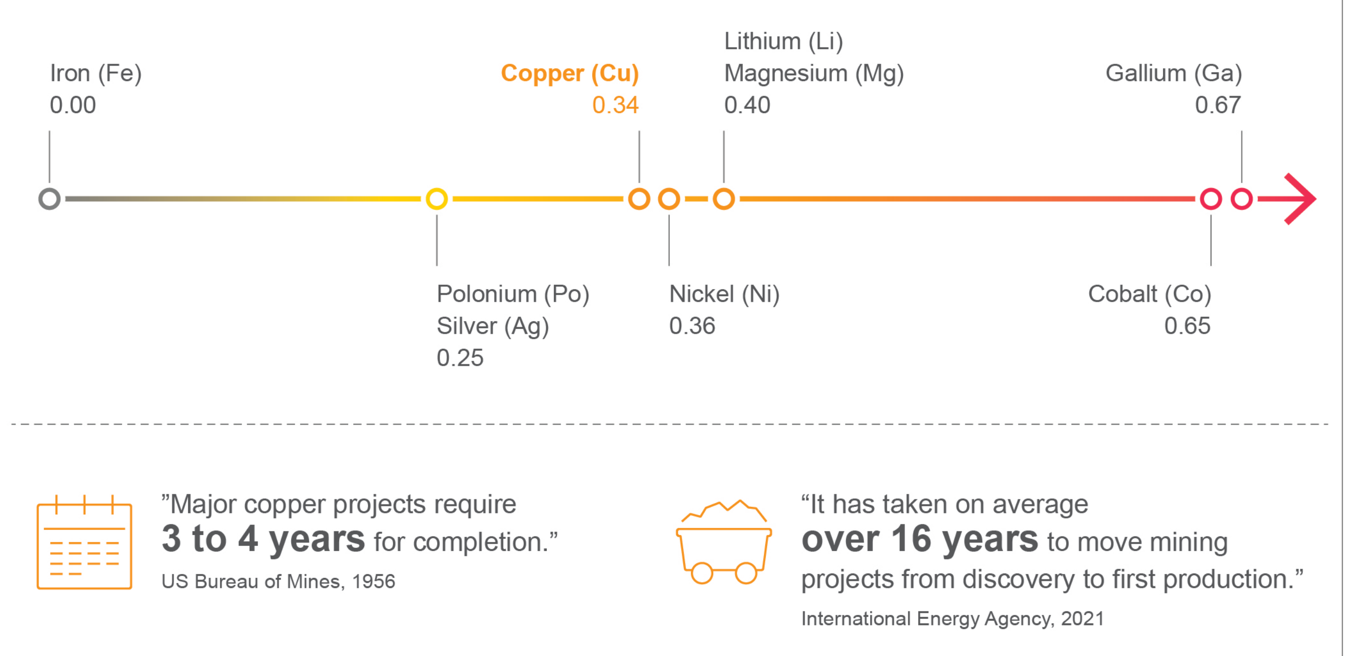
1. Climate change

Climate change will pose a challenge to the transition agenda and mining in particular. Drought, for example, would intensify competition for water among heavy industries, farmers, and households, with several countries likely to implement stricter requirements for the use of this resource. Rains, flooding, and wildfires will disrupt carefully calibrated logistics around mining operations. Meanwhile, protests driven by environmental issues continue to proliferate worldwide and will affect miners with frequent cargo and transport disruption. Extreme weather events are also likely to challenge aging port infrastructure critical to exports and could lead to severe disruption to supply. New multilateral frameworks could result in tighter regulations for mining, set targets of EV usages and carbon emission reduction, discourage the use of nondecarbonized supply chains, and lead to new restrictions for operating in environmentally sensitive areas.

2. Critical minerals policy

The energy transition will be shaped by the increased demand for batteries, mineral feedstocks, and the attendant supply chains. Sourcing these critical minerals comes with geopolitical scrutiny and risks. There is likely to be increased business uncertainty and unpredictability as governments intervene ad hoc on grounds of national interest, limiting foreign access to some of these minerals. There has been a significant acceleration of initiatives, particularly from the United States and the European Union, to make supply chains more resilient by diversifying sources of supply (principally away from China), including nascent moves to potentially increase domestic production and stockpiling of critical minerals. The USGS continues to score the relative criticality of these minerals, assigning each a "supply risk" score (see some minerals from the USGS May 2021 assessment below).[33] Although the US list does not include copper, the demand for this mineral and others will significantly grow and intensify competition among the major economies for influence in the countries that are their biggest source of copper.

The relative criticality of copper and evolving permitting landscape



Source: US Geological Survey, 2021

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3. Innovation

The most important—and most unpredictable—disruptor is innovation. Technological and engineering advances in mining could significantly lower the environmental costs of the industry, and/or reduce the supply-demand gap for copper if higher recycling rates, alternative materials, or usage efficiency of copper become viable for some of the demand generated by the energy transition.

33. Nassar NT, Fortier SM, "Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List," 2021, p.11, https://pubs.er.usgs.gov/publication/ofr20211045, accessed 16 June 2022.

For instance, advances in leaching, a technology for extracting copper from ore with chemical solutions, can unlock additional volumes, using less water and energy. In another example, the adoption of smelting capabilities that produce only oxygen as a by-product, for example, would eliminate GHG emissions from the process. The technology has been partially funded by state finances, but it is still in early stages. It would also take several years to get to scale, given the life cycle of typical mines—a much slower adoption than in computing technology for example. Even for individual mines, shifting to new technologies or processes is inherently slow—and costly. But new technology will also allow mining companies to comply with higher standards for tailings, requiring sturdier infrastructure and increased controls in the use of chemicals. There is also a major push for improving the technology and for scaling the recycling of discarded EV and mobile phone batteries, to re-harvest their metals.[34]

Overall, innovation could lower costs, increase supply, facilitate social license to operate, and bring new resources online. Alternatively, greater efficiency in the use of copper downstream, including higher recycling rates, could narrow the supply-demand gap.

34. Redwood Materials, founded by Tesla co-founder and former chief technology officer J.B. Straubel, is a case study for developing industrial scale in recycling. Tom Randall and Bloomberg, "Tesla co-founder has a plan to become king of EV battery materials—in the U.S.," Fortune Media IP Limited, 14 September 2021, https://fortune.com/2021/09/14/tesla-cofounder-jb-straubel-redwood-materials-battery-materials/, accessed 21 June 2022.

Chapter 9. Conclusion

The energy transition—a pathway toward transformation of the global economy to Net-Zero Emissions by 2050—will pose generational challenges for copper specifically and for the mineral industries at large. Energy transition will be enabled by new technologies for production and use of renewable energy sources. This in turn will require an enabling investment and policy environment to support innovation and increased production of the critical minerals needed to power these new technologies.

The demand for copper from energy transition is expected to peak in the mid-2030s, slow down in the 2040s, and see a modest increase by 2050. The overall demand for copper, however, will continue to increase owing to economic growth and growing world population, more than doubling from today's level. The 2050 climate objectives will not be achieved without a significant ramp-up in copper production in the near and medium term, which will be very challenging. The energy transition demand increase will be driven by the following:

- Deployment of EVs on a global basis
- Upgrade and build-out of the power infrastructure to support electrification
- Increase in renewable generation capacity including wind, solar, and energy storage

This energy transition demand will be particularly pronounced in the United States, China, and Europe. The supply system is entering the most challenging period as the global refined copper demand is projected to almost double from just over 25 MMt in 2021 to nearly 49 MMt in 2035, little more than a decade away. This surge will be driven in large part by energy transition end markets, which will nearly triple in size from 2021 to 2035 to nearly 21 MMt.

In the High Ambition Scenario, refined copper production is projected to increase from 24.5 MMt in 2021 to over 47 MMt in 2035. This results in chronic shortfalls between copper and supply demand beginning in 2025 and lasting through most of the 2030s, including a shortfall of more than 1.5 MMt in 2035 alone. But this scenario hinges on very significant increases in both capacity utilization and recycling rates. High Ambition is a highly optimistic scenario. What this scenario demonstrates is that, even at the outer edge of what could happen in copper mining and refining operations, there will not be enough supply to meet the demand identified for Net-Zero Emissions by 2050.

The Rocky Road Scenario is grounded in the realities of today's global industry, with all the obstacles and challenges identified in previous pages. Capacity utilization and recycling continue at the average rates of today, girded by the continuing operating and investment challenges that are endemic today. Under the Rocky Road Scenario, the annual supply shortfalls reach nearly 10 MMt in 2035—a vast amount that the market would be compelled to balance with unprecedented shocks on the demand- and supply-side. In this scenario, there would be a chronic shortfall from 2024 onward.

Notably, neither scenario assumes that the growth in new capacity—expansions and new mines—speeds up. Absent a major policy shift, however, regulatory, permitting, and legal challenges, combined with long timelines for new mines to come onstream, will continue to dampen the pace of supply increases.

This supply-demand gap for copper will pose a significant challenge to the energy transition timeline targeting Net-Zero Emissions by 2050. The challenge will be compounded by increasingly complex geopolitical and country-level operating environments. These include

- The strategic rivalry between the United States and China—over a projected period in which China will remain the dominant global supplier of refined copper, while the United States depends on imports for well over half its copper.
- Russia's invasion of Ukraine and its cascading effects on the commodities markets and energy security, which have highlighted the vulnerability of supply chains. "Supply chain resilience" policies aiming to secure reliable supplies of the materials needed for energy transition—and economies in general—are likely to be a central feature of the emerging geopolitics.
- A growing tension between energy transition, social license, and ESG objectives that dramatically increase the need for minerals like copper on one hand, while raising the compliance, legal, and operational costs of mining those minerals on the other.
- The risk of a significant, structural increase in copper prices as the supply-demand gap increases, with a potentially destabilizing impact on global markets and industry. While structurally higher prices incentivize international investment in new capacity, governments in sourcing countries are likely to seek to capture domestically a rising share of revenues.
- The fragmenting of globalization and a resurgence of resource nationalism.

The resulting challenge for all actors involved with the energy transition will be to manage often competing and seemingly contradictory priorities. It is clear that technology and policy innovation will both be critical to reducing the supply-demand gap for copper in order to help enable the net-zero goals. To achieve this, partnership between governments, producers and end users will be critical. Three priority areas stand out for exploration and further refinement in light of the findings of this study:

- **Technology:** Innovation that enables cleaner extraction and refining of copper will help address several of the critical challenges currently driving the supply-demand gap, including the carbon footprints of the copper industry itself as well as the ability to secure permits for new production. Innovation that enables greater efficiency in the use of copper and in recycling and/or the use of alternative materials that can reduce the current demand projections would also be critical contributions to reducing the gap.
- **Policy:** Clearer, stable, and predictable policies around permitting timelines and investment—required given the long development times—will help address some of the social license and political issues that will create delays in securing new copper resources for the market.
- **Interdependencies:** The energy transition will not only require more copper but also many other critical minerals. Some of these are already included under some governments' initiatives—particularly in the United States and the European Union—while others are

not. Understanding these wider interdependencies will be important to ensure that the path forward is not blocked by similar issues emerging for other key minerals required for increased electrification

Copper is essential to any successful energy transition. But the looming supply-demand gap risks short-circuiting the energy transition. Unless new supply for the metal of electrification comes online in a timely way, with clear political support and strategic commitment, Net-Zero Emissions by 2050 will likely remain out of reach.

Appendix A. Copper and the United States

- Current US policy and permitting copper mines
- Copper policy and permitting in global context

Appendix A. Copper and the United States

Copper was a business in the United States well before electricity. In colonial times, coppersmiths and brass founders made everything from pots and pans to bells and cannons. As already noted, Boston metal worker Paul Revere is famed for his midnight ride in 1775, alerting local militia to the approach of British troops at the beginning of the American Revolution. He is less well known as an entrepreneur and pioneer in copper, taking the lead in the United States to manufacture copper rolls to sheath ship hulls.

Large-scale American copper production began in Michigan, Minnesota, and Montana—the Lake Superior and Butte deposits—and spread southwesterly to Arizona and Utah. Mines were also developed in Alaska and other states. The United States dominated not only world mining but also smelting and refining to such an extent that the Bureau of Mines described the nation's role during World War I as "the clearing house for world copper."[1] Many technical innovations saw broad deployment in the American mining sector. World War II also evinced ready access by the Allies to abundant Western Hemispheric copper supplies for the manufacturing of munitions and other military equipment.

Today, development of copper mining is balanced against politics and extensive litigation. Permitting has become an ever-longer and more-contentious process, which is very different from the historical pattern. The US government actively supported the American copper mining sector for much of the 20th century.[2] Copper fell under conservation, price, and allocation controls during World War II and the Korean War, and at various times was subject to excise taxes, import taxes, tariff negotiations, and export controls. Copper was included in the emergency reserves established by the Strategic and Critical Materials Stock Piling Act of 1946, where it was alternately prioritized and de-prioritized depending on evolving economic and geopolitical conditions.

Moreover, under the Defense Production Act of 1950, the US government directly financed the copper industry through lending, price floors, and official procurement. This powerful law further enabled the financing of exploration for new copper deposits. In 1985, Congress directed the US Treasury Department to oppose any financing provided by multilateral development banks (e.g., the Asian Development Bank) and international financial institutions (e.g., the International Monetary Fund) for foreign sources of copper mining, smelting, and refining.[3] The US Overseas Private Investment Corporation was also subjected to restrictions on copper financing.[4]

Current US policy and permitting copper mines

Federal policy: Indirect and incidental

In contrast to much of the 20th century, there is no explicit US copper policy today, though copper is impacted indirectly and incidentally. A vestigial law that remains on the books describes

1. A. D. McMahon, Copper: *A Materials Survey* (US Department of the Interior, 1964), p. 32.

2. H. J. Schroeder, "Copper," *Mineral Facts and Problems*, 1975 Edition (US Department of the Interior, 1976), pp. 302-303. See also McMahon, pp. 313-321.

3. Section 501 of Title I of the Supplemental Appropriations Act of 1985 (P.L. 99-88), codified in the note at 22 U.S.C. 262k.

4. Section 7 of the Overseas Private Investment Corporation Amendments Act of 1978 (P.L. 95-268), repealed in Section 8 of the Overseas Private Investment Corporation Amendments Act of 1981 (P.L. 97-65).

copper as “vital to the national security and wellbeing of the United States,” but it requires no specific actions to be taken and has lapsed.[5] Indeed, copper is no longer subject to any significant trade restrictions, new exploration is no longer federally financed, and all programs intended to provide broad economic support to the copper industry—lending, price floors, and procurement—are defunct.

Copper is included, nonetheless, in broader development and tax policies that are not specific to it but that apply generally to categories of extractive industry. Copper mining on public lands, for example, falls under the same legal structure as other “hard rock” minerals (e.g., gold and silver). Copper, alongside gold, silver, and iron ore, is eligible for a percentage depletion tax preference rate of 15%, alongside additional tax preferences that are generally available to businesses (i.e., manufacturing deduction, accelerated depreciation) or specifically available to the mineral extractive sector (i.e., expensing of exploration and development costs, deduction for closing and reclamation).[6] No tax preferences are specific to the copper industry.

Despite the absence of a general copper program, many laws implicate the metal incidentally. Steel alloys that contain more than 0.6% copper are considered “specialty metal” by the US Department of Defense, and its official procurement channels must “Buy American.”[7] The US Intelligence Community is required by law to assess the North Korean regime’s revenue generation from trade in a basket of metals, among which copper is one, and sanction designations against individuals who trade in these metals are mandated by law.[8] The regular production by the US Mint of collectible coins to commemorate events, people, and organizations requires the frequent enactment into law of various numismatic mandates—specifying design, denomination, and alloy, including copper content requirements.[9] The US Food and Drug Administration also specifies that every 100 kilocalories of infant formula must contain at least 60 micrograms of copper.[10]

Above-ground risk: The crucial role of federal permitting

The permitting and litigation process determines the speed at which a mine will be developed or whether it will be developed at all.

After a developer locates a mineral deposit and deems its extraction to be economically sound, the permitting process begins. Constructing a new mine is akin to establishing a brand-new town, involving the daily movement of hundreds of trucks, airplanes, helicopters, drones, automobiles, and workers over the course of several years covering thousands of acres. Depending on a project’s

5. Section 2(a)(1) of the Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988 (P.L. 100-680), codified at 15 U.S.C. 5101. This is a prefatory statement in the law. Congressional findings of this type are formal declarations technically enacted into law without tangible force. As amended, this law only authorizes a research and development program through 2012 and, as its title suggests, is focused primarily on steel and aluminum. The legislature’s assertion of copper’s “vitality” does not trigger any federal actions on its own.

6. 26 U.S.C. 613(b)(2).

7. 10 U.S.C. 2533b. The Buy American provision is subject to various exceptions.

8. Section 6729 of the National Defense Authorization Act for FY 2020 (P.L. 116-92). For the mandatory designations, see also 22 U.S.C. 9214(a)(10). The other metals include gold, nickel, rare earths, silver, titanium, vanadium, and zinc.

9. The typical breakdown is 90% silver and 10% copper, but gold is also included on occasion. For examples in the past decade, see the Boys Town Centennial Commemorative Coin Act (P.L. 114-30), the World War I American Veterans Centennial Commemorative Coin Act (P.L. 113-212), the March of Dimes Commemorative Coin Act (P.L. 112-209), the Mark Twain Commemorative Coin Act (P.L. 112-201), the Lions Clubs International Century of Service Commemorative Coin Act (P.L. 112-181), and the National Baseball Hall of Fame Commemorative Coin Act (P.L. 112-152).

10. 21 CFR 107.100.

location, a variety of federal, state, tribal, city, and county laws; regulations; and ordinances may apply. Authorizations related to air quality, groundwater protection, surface water discharge, water use, reclamation and closure, hazardous waste, noise, telecommunications, highway safety, land use, zoning, and similar classes of permits are typically enforced at the state and local level with the framework of compliance defined by federal law.

State agencies are further empowered when federal statutes authorize federal agencies to delegate their authority for implementation and enforcement by the states. For example, the US Environmental Protection Agency routinely delegates its Clean Air Act permitting authority to state-level departments of environmental quality.[11] State governments may also often adopt regulations that are more stringent than federal rules, but not less.

The federal government is usually directly involved throughout the permitting or plan of operations process. This is always the case if the mineral deposit is located on federal land, which will typically be administered by the US Bureau of Land Management or the National Forest Service. It is also the case when federal land may be impacted by the placement of mine facilities on federal land even if the underlying deposit is located on state or private land. Further, mine development—tailings, discharge, etc.—often involves impacts to waters of the US, in which cases the US Army Corps of Engineers and the Environmental Protection Agency are automatically implicated. Federal permitting agencies are often required to take actions even in cases in which significant consequences to the environment are not expected, if for no other reason than to verify that this is the case.

The primary statute requiring federal agencies to assess the environmental and related social and economic effects of their proposed actions, including authorization of hard rock mine proposals under other federal laws, is the National Environmental Policy Act (NEPA).[12] Under this law, federal authorities may conclude that a federal action is categorically excluded from review—an outcome that is unlikely for hard rock mining projects—or they may complete an environmental assessment that results in a finding of no significant impact, which concludes the process. If the federal agency cannot conclude that there are no significant impacts, then the NEPA process requires a comprehensive review of a proposed project's significant impacts to the environment, including air, water, soil, vegetation, wildlife, public health, scenic views, grazing, and cultural and tribal values, as well as other issues raised during public scoping or Tribal Consultation. This review produces a massive—typically multi-volume—document called the Environmental Impact Statement (EIS) that forms the basis for a Record of Decision on the underlying permit application. Agencies undertake their own analysis; seek input from the community, Native American tribes, and other agencies; and identify alternatives to the proposed project to address the issues raised. Alternatives that could be considered by the federal agency include not proceeding with the project altogether, reducing its scope, modifying specific components (e.g., the number of facilities, the location of access routes, type of technology, etc.), and proposing mitigation measures to address the issues that are identified. If an EIS is required under NEPA, the EPA also has the authority under Section 309 of the Clean Air Act to review the EIS of other federal agencies and to comment on the adequacy and the acceptability of the environmental impacts of the proposed action.

11. 42 U.S.C. 7410-7412.
12. The National Environmental Policy Act of 1969 (P.L. 91-190), codified at 42 U.S.C. 4321 *et seq*.

An EIS is prepared by a designated lead agency with support from other federal agencies, state and local agencies, and tribal authorities. A typical NEPA process would commence following a project proponent submitting its “plan of operations” to the Bureau of Land Management or the National Forest Service. Each of these federal agencies have regulations and guidance documents that identify the requirements for authorization of a hard rock mine under a plan of operations. The US Army Corps of Engineers may also consider an application for a permit to discharge to waters of the US, including wetlands (“404” permits), for example, and the US Fish and Wildlife Service would review impacts to endangered or threatened species and critical habitats under the Endangered Species Act. Many mining projects entail rights of way and land exchanges, potentially involving other agencies not otherwise directly impacted. Consultation, coordination, and collaboration with Native American tribes is a requirement of all federal agencies prior to issuing a final decision when tribal lands are impacted. The White House and State Historic Preservation Offices are also consulted in connection with federal action under the National Historic Preservation Act.

Interest groups, protests, and litigation often target the federal permitting process. An agency’s determination of a Categorical Exclusion or a Finding of No Significant Impact can be challenged in court. Turnover from one executive administration to the next may also result in changes to earlier determinations. An EIS can be deemed incomplete or otherwise deficient by the court. Cooperating agencies may object to the outcome or change direction after a political election, as the NEPA process does not enforce agency cooperation. Federal permits, licenses, or other authorizations cannot be issued before the NEPA process is complete and can be revoked or suspended if the EIS is later deemed insufficient. They can also be revoked due to a change in politics, and policy can be revoked years after issuance (i.e., Clean Water Act 404 permits). It is not difficult to block a new mine.

As noted earlier, the International Energy Agency (IEA) estimates that more than 16 years are required to fully develop a mine, measured as the time between the discovery of the underlying deposit and the first mineral production.[13] The IEA does not provide any supporting data for this estimate, but it appears to be a global average and applies to all minerals, not just copper. In the case of the United States, 16 years is likely a significant underestimate. Many projects fail during the permitting or litigation process, making them difficult to count, and many mines are essentially expansions of previous operations from as far back as the 1890s, if not further. With only five copper mines seeing first production in the 21st century and another five working through the permitting process now, computing averages rigorously is impossible. In any event, discovered deposits often wait decades before permits are even sought. The projects most likely to move from discovery to production are those with strong state agencies leading the environmental review and with limited federal footprint in terms of land ownership and other NEPA-triggering equities.

US copper industry: Current and prospective

The existing “fleet” of US copper mines producing today can be characterized in several ways. There are approximately 25 such mines in total, though less than 20 are significant producers. The vast majority of US copper production occurs in the Southwest region of the United States. Most

13. IEA, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021), p. 12: https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf, accessed on 21 June 2022.

copper mines have a production capacity of less than 100,000 metric tons per day, suggesting it is easier to finance, build, and permit a smaller mine than a larger one.

Age is more difficult to ascertain. New deposits are more likely to be discovered next to existing deposits, new mines are more likely to be constructed next to old mines, and old mines can be refurbished into new mines. The underlying deposits of most US copper mines were explored and developed in the 19th and 20th centuries, long before the passage of the National Environmental Policy Act. Detailed Records of Decision may not always exist. Determining precise "start dates" can be nearly an impossible task in areas where production began long before modern law arrived, where states had not yet even been admitted to the union. Nonetheless, we can observe that most existing mines are projects that extend over generations.

Existing mines, or new mines that build upon previous operations, benefit from a higher degree of regulatory certainty than greenfield projects. Regions where substantial production has already occurred are likely to see fewer novel impacts to the environment that have not already been felt or otherwise mitigated. In addition, federal and state agencies may be more reticent to take actions that threaten jobs, even if they may be more willing to take actions that make it more difficult to create new ones. Regulatory uncertainty for new mines also places a premium on increasing efficiencies and extending the life of existing mines whenever possible.

Relationship between copper production and federal land ownership

State	Mining capacity (thousand metric tons per year)	State share of national total (percent)	Share of land federally owned (percent)
Arizona	1,329	70%	39%
Utah	220	12%	63%
New Mexico	190	10%	32%
Nevada	95	5%	80%
Montana	40	2%	29%
Michigan	25	1%	10%

Source: US Geological Survey, Congressional Research Service

Geology may explain why US copper production is found principally in the Southwest, but land ownership explains why a federal authorization that includes a NEPA review will almost certainly be required for the development of any new US copper mines. The federal government owns approximately 27% of the US land area.[14] The 11 Western states comprise 40% of the Lower 48 acreage, and 46% of their land is owned by the federal government. Additionally, the federal government owns almost two-thirds of Alaska. Of the top-six copper-producing states—Arizona, Utah, New Mexico, Nevada, Montana, and Michigan—the federal share of land ownership ranges from a low of 10% to a high of 80%. If the development of the deposit could impact federal lands—including those administered by the National Park Service, the National Forest Service, the US Fish and Wildlife Service, the Bureau of Land Management, or the Defense Department—then a NEPA review is required. Between them, these five agencies manage more than 600 million acres in federal land, excluding non-state US territories (e.g., in the Pacific Ocean or the Caribbean).

14. *Federal Land Ownership: Overview and Data*, Congressional Research Service (R42346).

The United States has already undergone significant exploration, but much of this occurred in the preceding century with techniques then available. The US Geological Survey estimates that only one-third of the country has been "mapped at the detailed scales required for mineral exploration."[15] While it is possible that substantial copper deposits may exist in undeveloped portions of the country, they are most likely to be developed nearby current sites of production for a host of geological, economic, and political reasons. Absent a fundamental change in the process of obtaining federal authorization, including NEPA, even major new discoveries of copper are unlikely to yield significant increases in domestic mining. Deposits on state and private land with minimal federal equities may potentially face an easier regulatory path to development, but even supportive state and local governments are no guarantee of ultimate success.

A handful of case histories illustrate the challenges of navigating the US permitting and litigation process, as well as 2–4-year political cycles. The Rosemont project in Arizona, for example, launched its environmental review led by the US Forest Service in 2008 and completed it in 2013, but still waited four years to obtain its affirmative record of decision in 2017; a parallel permit from the US Army Corps of Engineers was issued in 2019, but was suspended later that same year. The NorthMet project in Minnesota underwent a 10-year-long environmental review by both federal and state agencies, resulting in an approved permit in 2015, but still has not commenced construction due to ongoing litigation. The Environmental Protection Agency may even notify ESG-related stakeholders that they have an opportunity to sue to slow or stop projects already under review by other federal agencies. These are only a few examples from the myriad of projects that are currently negatively impacted by the US permitting process.

Copper policy and permitting in global context

Potential domestic changes to US policy

Three domestic motivations may drive substantial change in US copper policy with varying impact, alternately favorable and unfavorable to copper's prospects. First, proponents of mineral extraction might succeed in amending existing laws to expedite the permitting process for copper mines. There are continuing efforts, including proposed legislation in Congress, to streamline permitting for everything from mining to renewable wind projects. Given the strength of environmental opposition, however, this is unlikely to occur in terms of mining.

Second, opponents of mining could succeed in amending laws and revising regulations to create an environment that is even less conducive to mineral extraction than exists already. One mechanism by which this could occur is the elimination of existing tax preferences for the extractive industries, including copper. The system by which mineral claims are "patented"—holding title to surface and mineral rights—has been subject to a moratorium since 1994. An early House of Representatives version of the stalled Build Back Better Act would have imposed a royalty of 8% on new mines and of 4% on existing operations. This provision was not included in the version that passed the House in November 2021 or the version the Senate has considered. Other measures, such as imposing additional reclamation fees, have been proposed over the years, and the repeal of tax preferences is often discussed. Though none of these proposals are specific to copper, copper mines would be impacted. Far less likely mechanisms would include the outright

15. Dr. Murray Hitzman, Associate Director, Energy and Minerals, US Geological Survey, in testimony before the Senate Committee on Energy and Natural Resources (March 28, 2017).

banning of hard rock mining on federal lands. Regulatory agencies, which are subject to political direction, could also push the limits of their existing authority without needing any additional legislation, as courts routinely defer to an agency's interpretation of its regulatory powers delegated by Congress.

Finally, new policies could be adopted to increase domestic copper production for the purpose of protecting vulnerable supply chains. Recent legislation makes several billions of dollars in federal financing available for rare earth and battery metal production, processing, recycling, and research and development, and mandates new mapping and market outlook analysis for critical minerals generally.[16] Projects related to clean energy minerals directly tied to renewable, battery, and nuclear technology are also eligible for Department of Energy loans and loan guarantees.

Strategic competition

A fourth and final motivation for US copper policy reform may be the current competitive strategic environment.

According to the US Geological Survey, approximately 60% of world reserves are in six countries: Australia, Chile, Mexico, Peru, Russia, and the United States.[17] By far, the largest is Chile, with almost 25% of world reserves.

Strategic competition could also support greater US domestic production. Copper has not featured prominently in federal policy discussions concerning "critical minerals" despite the reliance on imports and association between copper and critical minerals. It is eligible for inclusion in the National Defense Stockpile, maintained by the Defense Logistics Agency, but no equivalent civilian stockpile exists. Pursuant to Executive Order 13817, such minerals—rare earths, battery metals, platinum group metals, etc.—are generally defined as those vulnerable to supply disruption, vital to American economic and national security, and upon imports of which the United States is heavily reliant.[18] Copper was not included in either the 2018 or 2021 Critical Minerals Lists developed by the US Department of the Interior (in the latest agency modeling, copper garners a "supply risk" score of 0.34 on a scale from 0.00 to 1.00, just 0.06 away from the minimum cutoff of 0.40.).[19] There is discussion for the metal's inclusion in the Critical Minerals List.

Inclusion on the Critical Minerals List does not trigger any federal action—no funding, no procurement, no lending. Nonetheless, Defense Production Act authorities previously used to support the copper sector after World War II are occasionally used to support certain aspects of the rare earth value chain. The Commerce Department is also conducting a Section 232

16. See Title VII of Division Z of the Consolidated Appropriations Act, 2021 (P.L. 116-260), and Title II of Division D of the Infrastructure and Investment Jobs Act (P.L. 117-58).

17. US Geological Survey, *Mineral Commodity Summaries* 2022.

18. Executive Order 13817, "A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals," 82 FR 60835 (December 20, 2017): https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals, accessed on 21 June 2022.

See also Executive Order 13953, "Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries," 85 FR 62539 (September 30, 2020): https://www.federalregister.gov/documents/2020/10/05/2020-22064/addressing-the-threat-to-the-domestic-supply-chain-from-reliance-on-critical-minerals-from-foreign, accessed on 21 June 2022.

19. US Geological Survey, Methodology and Technical Input for the 2021 Review and Revision of the US Critical Minerals List (Open-File Report 2021-1045), p. 11 (Figure 3): https://pubs.usgs.gov/of/2021/1045/ofr20211045.pdf, accessed on 21 June 2022.

investigation into US import reliance for rare earths, which, depending on the results, could result in various types of trade remedies. In the future, federal departments and agencies could voluntarily, or be required to, base similar actions on a commodity's criticality designation. Mainland China's market dominance of smelting and refining will also feature into US policy debates and may provide more impetus for federal policies that boost processing capabilities, either domestically or at least in the Western Hemisphere.[20] For example, in 2022, the United States announced its intention to use powerful Defense Production Act authorities to support the production and processing of battery metals, building off previous efforts to classify rare earth elements under the same authorities and to reorient the Department of Energy's Loan Program Office to finance green energy-related minerals.

Finally, the federal government is increasingly asserting that climate change is an "existential" threat facing the world. Given the centrality of copper to renewable energy technologies and electrification, Washington could use national security authorities to promote copper production, either domestically or internationally, for redefined energy security purposes. Net import reliance over 50% also merits inclusion on the critical minerals list; copper, as of 2021, was at 45%.

The US Geological Survey is a technical agency within the US Department of the Interior. Its methodology may strongly suggest exclusion or inclusion of a mineral, but ultimate decision-making authority rests with the Secretary of the Interior. The Survey assessed the supply risk of a basket of mineral commodities and scored copper (on a scale of 0 to 1) at 0.34. In contrast, nickel scored 0.36 and beryllium scored 0.33.

USGS methodology applied to minerals below the criticality threshold

Mineral commodity	Mean score (0 to 1) Minimum for inclusion: 0.40	Included on critical minerals list?	Vulnerable to single point of failure?
Nickel	0.36	Yes	Yes
Copper	0.34	No	No
Beryllium	0.33	Yes	Yes

Source: US Geological Survey

All three of these scores are below the threshold of 0.40. Nickel and beryllium are included in the latest version of the Critical Minerals List, nonetheless, because US supplies of these two minerals are vulnerable to "single points of failure." This distinction merits automatic inclusion based on the latest methodology.

20. https://www.nytimes.com/2022/03/31/business/economy/biden-minerals-defense-production-act.html, accessed on 21 June 2022.

Appendix B. Methodology and approach

- Energy transition demand
- Nonenergy transition demand and supply
- Operational challenges methodology

Appendix B. Methodology and approach

Energy transition demand

S&P Global energy scenarios

Multitech Mitigation

The S&P Global Multitech Mitigation (MTM) scenario (also referred to as “net-zero scenario”) is built on the premise of determining the energy requirements of meeting the Paris Agreement goal of limiting the average global temperature rise to 1.5°C above preindustrial times by the end of the century, and therefore reaching Net-Zero Emissions by 2050 as outlined in *Chapter 3. Copper requirements in the energy transition* in the main report.

This net-zero scenario is based on a different approach from the standard, bottom-up and forward-looking S&P Global scenarios—Inflections, Green Rules, and Discord for instance (the three of which are explained later in this section). The MTM scenario, by definition, begins with a predetermined outcome and works backward using modeling as the primary basis of construction, rather than evaluating the interconnectedness of the geopolitical, macroeconomic, and policy landscape and how they impact the energy system. Achieving a state of net zero requires radical actions that are not currently planned. The key elements of this scenario are as follows:

- **Existing energy and industry system infrastructures are large and complex and adjusts slowly.** Time is needed for the world to transition under the effects of new stricter policies and behaviors. To achieve this “bridge,” the net-zero scenario largely follows the Green Rules scenario assumptions and pathways through the late 2020s, after which it diverges, allowing each path to reach its targets in different ways and at different times. The approach taken in the net-zero scenario is different from other scenarios that often assume immediate change in energy use and emission levels.

- **Diversification of energy supply and electrification based on renewable capacity (mainly wind and solar) in power generation is emphasized.** The power sector needs to shift from a mostly fossil fuel–based system to a clean electricity generation system, relying primarily on renewable energy resources. The scenario relies heavily on the development of solar photovoltaics (PV), wind, and battery storage but also considers a nuclear renaissance with increased nuclear use by 2050.

- **The use of carbon capture and storage (CCS) is expected to rise in the medium term, but the ultimate scale and longevity of this expensive technology—and its acceptability as a tool that prolongs dependence on hydrocarbons—are still unknown.** The MTM scenario, while inclusive of some CCS, focuses on faster electrification of the economy and strong fuel switching out of hydrocarbons.

- **Strong government mandates and policies are implemented between 2022 and 2026, along with high carbon prices and coordinated markets beginning in the 2030s.** A focus on reducing methane emissions achieves dramatic results that accelerate after 2030.

- **The concerted global effort to reach Net-Zero Emissions by 2050 is pan-industry.** Emissions from nonenergy sectors such as industrial, agriculture, and waste decline along with those from the energy sector.

Overall assumptions

- **GDP growth** rates generally follow Green Rules (see description in the next section), in which there is a slow start to recovery and lower overall growth compared with the base case, Inflections.

- **Strict policies, mandates, and standards are implemented in 2022–26.** The scenario is generally based on Green Rules assumptions that governments would need to play a heavy hand to create the radical moves needed to achieve net-zero emissions—and be willing to have their economies shoulder the costs.

- **Benchmark energy prices remain low.** The benchmark international commodity prices supporting the energy demand outlook are based on those developed for the Green Rules scenario, in which the combination of declining demand and ample supply leads to a long period of low prices.

- **Retail energy prices rise.** For emissions to decline, we assume that total implied energy costs must increase. Building on the Green Rules scenario benchmark prices, the MTM scenario removes retail price subsidies across all markets regardless of wealth, but in a phased way beginning in 2027. In the first five years, subsidies are removed for power and industry, and within 10 years subsidies are removed for the transport, residential, and commercial sectors. Importantly, the subsidies are eventually removed across the world, especially in areas with the strongest marginal source of energy demand.

- **Carbon prices are high.** High carbon prices are needed to incentivize deep decarbonization of industry, and a global market is required so that emission cuts occur in the most efficient manner possible while still protecting investment and jobs. There is global convergence of carbon markets by the mid-2030s. By 2040, the MTM scenario's average real 2020 price of $150 per metric ton of CO_2 is 50% higher than in the Green Rules scenario.

- **Many least-developed markets leapfrog technologies.** From 2035 onward, we assume a benefit from leapfrogging to new energy production and consumption technologies that have lower carbon content. This leapfrogging reflects lower technology costs that have been driven down by heavy investments like those made in renewable electricity technologies by wealthier economies since 2000. There is, therefore, an underlying assumption that new technology can be transferred successfully to developing markets, and restrictions due to intellectual property rights and other legal limitations can be overcome and mechanisms are developed to speed the transfer of technologies.

- **Total primary energy consumption is only about 5% less than in the Green Rules scenario by 2050.** Although there is improvement in energy efficiency over our faster transition scenario, the main tools used to get to Net-Zero Emissions by 2050 are a mix of energy choices and land use, land use change, and forestry (LULUCF) offsets. Specifically,

- **Power markets move steadily to decarbonize.** The MTM scenario is built on the assumption that efforts to decarbonize power sectors expand strongly across the world, moving beyond advanced markets to emerging markets within the next two decades and to least-developed markets later in the outlook. Over time, the result is a consistent stance on certain forms of power generation that can be developed and operated in given countries. It also leads to a very strong electricity demand outlook.

- **Transportation markets diversify with a combination of electricity, gas, hydrogen, and biofuels.** The scenario assumes that electric vehicles (EVs) have strong penetration into light- and heavy-duty vehicle sales and fleets around the world. Rail networks are also electrified, with a shift away from road haulage. There is also a mix of electrification, hydrogen, LNG, and biofuels in marine transportation—and a mix of electricity (short-haul) and hydrogen (long-haul) in aviation transportation.

- **Nuclear power enjoys a renaissance and is used for power generation and, in some cases, the production of green hydrogen.** While in the Green Rules scenario, nuclear power accounts for 8% of primary energy use; in the MTM scenario, it reaches more than 15% by 2050.

- **Energy efficiency is assumed to improve significantly over 2010–20 by a 1.5% annual reduction in energy intensity of GDP (British thermal units per real US dollars).** During the 2020s, efficiency improves to about a 2.3% annual reduction in energy intensity of GDP, by the 2030s it is accelerating to closer to a 3% annual reduction and then settling back to an average of a 2.3% annual reduction in the 2040s.

• **Methane emissions from energy-related sources decline rapidly starting in the 2030s.** Strong focus on the reduction of methane increases in the early 2020s. In the MTM scenario, mandates for elimination of methane release are enacted. By the mid-2030s, methane emissions drop to only 15% of their peak in 2019.

• **Nonenergy sector emissions** (agriculture, industrial processes, and waste) are reduced more severely in the net-zero scenario than in the Green Rules scenario. By 2050, agricultural emissions of 1,569 million metric tons of carbon dioxide equivalent (MMtCO_2e) are only 28% of the 5,659 MMtCO_2e in Green Rules.

• **Global greenhouse gas (GHG) emissions rise initially and then start to diverge below the Green Rules scenario from 2027 onward**, reflecting the benefit from strict policies introduced in the early 2020s that accelerate faster over the long term in the MTM scenario. The economic recovery from 2020 and inertia of the existing energy and nonenergy infrastructure cause emissions to rise for several years before beginning a slow decline. The impact of carbon prices, combined with government mandates and new policies to sharply reduce absolute carbon emissions, puts the global trajectory on a downward path by 2027.

Detailed assumptions

Fundamental assumptions

In the MTM scenario, the emphasis is on renewables and the multiple benefits of improved energy efficiency, complemented by wider supply diversification in the transformation and end-user segments.

CCS technology advancement does not progress in the MTM scenario owing largely to the intense policy and societal intent to minimize fossil-fuel use across all sectors, for all uses. In this scenario, CCS is viewed as an enabler of hydrocarbons and a technology to be used only as a last resort. In the MTM scenario, the preponderance of available renewable generation at low costs and further declines in the cost of electrolysis through innovation support the production of green hydrogen.

Fossil fuels retain only a 22% share of primary energy demand by 2050. Conversely, renewables increase its primary share to 43% (including hydro), with nuclear, biomass, and other smaller energy sources making up the rest. Energy-related emissions still are positive at approximately 5,816 MMtCO_2e, but nonenergy-related GHG emissions more than compensate with 6,435 MMtCO_2e captured. Negative emissions come from CCS and carbon sinks arising from land use changes (e.g., re/afforestation).

Carbon prices

Because this scenario focuses on regulations and standards to drive down energy consumption, there is reduced demand for carbon credits in a smaller carbon market, resulting in somewhat lower prices. Global carbon prices rise to $150 per metric ton of CO_2 (real 2020 dollars) by 2040 and $225 per metric ton of CO_2 by 2050.

Markets versus policies

In the MTM scenario, the government policies are the driver of the transition, with the emphasis on command-and-control regulations for energy efficiency. Mandated capacity additions and charging network expansions to shift the power and transport sectors' supply mixes are good examples of the contributions the government makes to drive the changes foreseen in this net-zero scenario. Government actions help create new markets, drive up private investments in those markets, and reduce their unit costs.

In this respect, governments are also deciding where to focus their efforts, which are assumed to be centered on creating the conditions for a range of different zero-carbon technologies to become mainstream. Government action is not aimed at CCS, as this is seen as supporting the incumbent fossil fuel–based system, which the wider society is not assumed to support. Governments feel obliged to support only zero-carbon technologies.

In this context, new companies are assumed to emerge to develop the new technologies that compete with incumbent fossil-fuel companies, and the MTM scenario does anticipate more, different players involved in the energy system. The externalities of GHG emissions are internalized in higher costs of capital equipment and goods, with consumers ultimately paying.

Electric power

In the MTM scenario, the ongoing renewables-focused capacity installation trend is increased in both scale and intensity. It is assumed that renewable costs decline and converge, bringing them into competition with both coal and gas levelized cost of electricity numbers before 2030. Improved cost competitiveness, backed by aggressive capacity addition mandates and thermal capacity retirement programs, leads to rapid power supply mix changes in advanced and then emerging markets.

The carbon intensity of power generation shifts steadily downward, and efficiency gains first slow and then reverse load demand growth. The moderately high carbon prices that are assumed provide a reinforcement for revenue streams in power production increasingly shaped by low-cost renewables. A more decentralized model of power production and consumption is assumed in the MTM scenario. New opportunities for flexible business models flourish, and nonenergy players are expected to bring focus on renewable electricity for many markets where barriers to entry are taken to be lower.

It is also assumed that this scenario includes more nuclear to push GHGs out of the base-load power mix. This especially applies to Asia, where load growth and opportunities for low-emissions generation will be broad. A more modular approach to nuclear generation is seen to further this objective. Fusion remains beyond current consideration.

Transport

The MTM scenario assumes (1) more efficiency from heavy-duty vehicles' internal combustion engines, (2) electrification, and (3) more rail in freight.

Shipping: In the MTM scenario, electrification is more prominent in shipping, supported by hydrogen.

Aviation: The MTM scenario assumes supply diversification opportunities for short-haul flights in the second half of the forecast period. Biofuels and hydrogen-fueled solutions are assumed to be cost competitive and reliable for long haul.

Hydrogen

The MTM scenario is the "green" hydrogen scenario, with the wider availability of renewables and improved fuel-cell technology leading to hydrogen being generated through electrolysis. Very little blue hydrogen is developed owing to policies aimed at ending the use of hydrocarbons in every practical way possible.

In the MTM scenario, hydrogen is developed as part of a wider distributed generation, with hydrogen generated in more diverse and remote locations around the world, forming the basis of support for islands of hydrogen distribution for backup power, local space heating needs, and transport networks.

Hydrogen becomes part of a decentralized, small-scale, low-cost system, based on new market entrants driving a radically different energy system. Technology development is rapid with many suppliers and with the technology benefiting from improvements in adjacent sectors: fuel cells for trucks, ships, and planes.

Biomass

Modern biomass (including biofuels, biogas, biowaste, woodchips, and wood pellets) demand more than doubles in absolute terms under the MTM scenario between 2020 and 2050. But this is against a backdrop of vast structural changes in energy supply. Biomass therefore also increases its overall share of primary energy demand, reaching approximately 10% by 2050, up from 5% in 2020. Carbon sinks arising from land use changes (e.g., re/afforestation) are an important contributor to offsetting GHG emissions.

Key indicators for MTM

		History		MTM
		2019	2020	2050
Real GDP	Billion 2020 US$	87,417	84,150	179,712
	Average growth	2.9%	2.7%	2.6%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy consumption	MMtoe	14,590	13,798	13,156
	Average growth	1.8%	1.5%	-0.2%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy intensity of GDP	Metric tons of oil equivalent per million 2020 US$	167	164	73
Primary energy shares	Oil	32%	30%	16%
	Gas	23%	24%	9%
	Coal	26%	27%	4%
	Nuclear	3%	3%	8%
	Hydro	5%	5%	30%
	Renewables*	2%	3%	8%
	Modern biomass**	5%	5%	7%
	Other***	4%	5%	0%
EV shares of LV market****	Sales	2.6%	4.4%	93.0%
	Fleet	0.5%	0.8%	86.0%
GHG emissions	Total ($MMtCO_2e$)*****	50,740	48,066	-115
	Energy-related ($MMtCO_2e$)	38,532	35,923	6,318
GHG emissions per GDP	Total ($MMtCO_2e$/US$ 2020)	580	571	-1
	Energy-related ($MMtCO_2e$/US$ 2020)	441	427	35

Note: Some values have been rounded. MMt = million metric tons; MMtoe = million metric tons of oil equivalent; CO2e = CO2 equivalent; LV = light vehicle.

*Renewables include solar, wind, geothermal, and tide/wave/ocean energy.

**Modern biomass includes biofuels in transport and biomass used in industry, power generation, district heating, and refineries.

***Other includes solid waste, traditional biomass (used in the domestic sectors; includes charcoal, wood, bagasse), ambient heat, and net trade of electricity and heat.

****EVs is a comprehensive term that refers to all fully and partially electrified vehicles, including battery electric vehicles (BEVs), fuel-cell electric vehics (FCEVs), hybrid electric vehicles (HEVs), mild hybrid electric vehicles (MHEVs), and range extended electric vehicles (REEVs). However, the term is often applied just to battery electric vehicles.

*****Total GHG emissions represent global nonenergy-related CO2, methane, and nitrogen oxide (NOX) emissions combined with CO2 and methane emissions related to energy production and use. For consistency, nonenergy and methane emissions have been converted to CO2e amounts to provide a total figure.

Source: S&P Global

Green Rules

The Green Rules scenario is an integrated global scenario, where very strong public support for change drives governments to implement policies and actions that foster robust private investment and innovation that leads to revolutionary changes in energy use and supply and moves the world much closer to the Paris Agreement compared with the Inflections scenario outlook.

The combined impacts of recurrent global crises have a fundamental impact on the world that supercharges social and political backlash and leads to strong demands for government action on security threats related to health, economic opportunity, and climate change. Reaction to the pandemic—and to the ongoing impacts of climate-related weather and environmental events—leads to fundamental changes in behavior and choices by individuals and institutions, transforming organizational operations and how people work, shop, play, vote, and communicate.

Key indicators for Green Rules

		History		Green Rules
		2019	2020	2050
Real GDP	Billion 2020 US$	87,417	84,150	183,346
	Average growth	2.7%	2.7%	2.6%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy consumption	MMtoe	14,590	13,798	14,833
	Average growth	1.8%	1.5%	0.2%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy intensity of GDP	Metric tons of oil equivalent per million 2020 US$	167	164	81
Primary energy shares	Oil	32%	30%	15%
	Gas	23%	24%	22%
	Coal	26%	27%	8%
	Nuclear	3%	3%	4%
	Hydro	5%	5%	8%
	Renewables*	2%	3%	26%
	Modern biomass**	5%	5%	9%
	Other***	4%	5%	8%
EV shares of LV market****	Sales	2.6%	4.4%	88.0%
	Fleet	0.5%	0.8%	55.0%
GHG emissions	Total ($MMtCO_2e$)****	50,740	48,066	25,391
	Energy-related ($MMtCO_2e$)	38,532	35,923	16,337
CO_2 emissions per GDP	Total ($MMtCO_2e$/US$ 2020)	580	571	138
	Energy-related ($MMtCO_2e$/US$ 2020)	441	427	89

Note: Some values have been rounded. MMt = million metric tons; MMtoe = million metric tons of oil equivalent; CO2e = CO2 equivalent; LV = light vehicle.

*Renewables include solar, wind, geothermal, and tide/wave/ocean energy.

**Modern biomass includes biofuels in transport and biomass used in industry, power generation, district heating, and refineries.

***Other includes solid waste, traditional biomass (used in the domestic sectors; includes charcoal, wood, bagasse), ambient heat, and net trade of electricity and heat.

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*****Total GHG emissions represent global nonenergy-related CO2, methane, and nitrogen oxide (NOX) emissions combined with CO2 and methane emissions related to energy production and use. For consistency, nonenergy and methane emissions have been converted to CO2e amounts to provide a total figure.

Sources: S&P Global and the International Energy Agency (IEA) for history; S&P Global for outlooks

In a new geopolitical twist, the concept of national security is enlarged and becomes strongly intertwined with countries' efforts to mitigate climate change. This drives them to double down on their ambitions to pursue net-zero targets and to dominate clean energy technologies and industries across the value chain, setting up a new type of "climate technology race" that results in an increasingly competitive global landscape.

Although the geopolitical landscape remains challenging, greater international cooperation is demanded to ensure progress on global efforts to address all security concerns—particularly climate change. National efforts alone are no longer deemed acceptable.

Financial institutions, investors, and nongovernmental organizations (NGOs) are strong actors in pushing companies and governments toward faster action through environmental, social, and governance (ESG) measures. This concept rapidly evolves to become the standard upon which all investors and companies measure and chart success.

The world does not reach Net-Zero Emissions by 2050, but global GHG emissions are more than 45% lower than 2020 levels, at about 25 billion metric tons of CO_2e. This is driven by a drop of energy-related emissions by half to just over 16 billion metric tons, which amounts to the world being on a pathway to an average global temperature rise of 1.9°C by 2100.

The transition to a lower GHG emission pathway and fundamental changes in the global energy landscape comes at an enormous economic and social cost. People, companies, infrastructure, and whole industries are made redundant, with significant investments required to replace the old and grow the new.

Inflections

The Inflections scenario represents a more conservative future, where fossil fuels will continue to hold a key role in the energy system and the economy. It considers fundamental turning points in government, corporate, and individual choices and behavior away from fossil fuels and toward a move to a greener world—but also limits the realization of climate goals.

The COVID-19 pandemic is seen as an "accelerator" of many of these changes, some of which had been under way for some time, but become primary drivers of global political, economic, and business affairs in the years to come.

National net-zero goals by governments reflect a marked increase in ambitions to address climate change, but rhetoric often outweighs actions. For most governments, addressing climate change is only one of many concerns, including national security and economic interests. The degree to which leaders are willing or able to take the steps necessary to support national and global efforts to mitigate climate change varies greatly.

ESG investment assessments are key standards for financial reporting and strategy for many companies, resulting in the private sector often leading change when the government falters. There is, however, a divergence in the impact that ESG methodologies have on publicly listed companies and financial markets in advanced economies versus state-owned companies and banks in other countries.

People emerge from the pandemic with aspirations to do more to support actions to address future health threats and the challenges of climate change. However, public support for significant action remains fickle, with scant willingness by many to bear the full financial and social costs necessary to realize their own governments' climate-related ambitions.

The world is multipolar, with more diffuse geopolitical power and national interests that often constrain efforts toward global collaboration. As a result, the national interests of major powers are never aligned to cut emissions significantly enough to meet most stated national and global goals.

Key indicators for Inflections

		History		Inflections
		2019	2020	2050
Real GDP	Billion 2020 US$	87,417	84,150	187,981
	Average growth	2.9%	2.7%	2.7%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy consumption	MMtoe	14,590	13,798	17,178
	Average growth	1.8%	1.5%	0.7%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy intensity of GDP	Metric tons of oil equivalent per million 2020 US$	167	164	91
Primary energy shares	Oil	30%	30%	25%
	Gas	24%	25%	25%
	Coal	27%	21%	13%
	Nuclear	3%	3%	3%
	Hydro	5%	5%	6%
	Renewables*	3%	6%	15%
	Modern biomass**	5%	5%	6%
	Other***	5%	5%	6%
EV shares of LV market****	Sales	2.6%	4.4%	70.0%
	Fleet	0.5%	0.8%	42.8%
GHG emissions	Total ($MMtCO_2e$)****	50,740	48,066	42,555
	Energy-related ($MMtCO_2e$)	38,532	35,923	29,410
CO_2 emissions per GDP	Total ($MMtCO_2e$/US$ 2020)	580	571	226
	Energy-related ($MMtCO_2e$/US$ 2020)	441	427	156

Note: Some values have been rounded. MMt = million metric tons; MMtoe = million metric tons of oil equivalent; CO2e = CO2 equivalent; LV = light vehicle.

*Renewables include solar, wind, geothermal, and tide/wave/ocean energy.

**Modern biomass includes biofuels in transport and biomass used in industry, power generation, district heating, and refineries.

***Other includes solid waste, traditional biomass (used in the domestic sectors; includes charcoal, wood, bagasse), ambient heat, and net trade of electricity and heat.

****EVs is a comprehensive term that refers to all fully and partially electrified vehicles, including battery electric vehicles (BEVs), fuel-cell electric vehics (FCEVs), hybrid electric vehicles (HEVs), mild hybrid electric vehicles (MHEVs), and range extended electric vehicles (REEVs). However, the term is often applied just to battery electric vehicles.

*****Total GHG emissions represent global nonenergy-related CO2, methane, and nitrogen oxide (NOX) emissions combined with CO2 and methane emissions related to energy production and use. For consistency, nonenergy and methane emissions have been converted to CO2e amounts to provide a total figure.

Sources: S&P Global and the International Energy Agency (IEA) for history; S&P Global for outlooks

Discord

The Discord scenario begins in a world fractured by the disparity of success of vaccine programs around the world and their ongoing failure in many countries. New variants of the COVID-19 virus continue to spread, putting significant new strains on emerging country health systems and raising fears of more lockdowns throughout the world. It becomes evident to many people and leaders that the global health crises will persist for some time and remain a constant threat to national economic recoveries and personal well-being. This situation sustains a strong sense of fear and defensiveness in the Discord scenario that reorders the priorities of political leaders toward increasingly isolationist policies that steadily corrode geopolitical cooperation. Rather than a rapid return to precrisis economic and political trends and pathways, we forecast a flow of defensive, often hostile language and policies by governments and political leaders that contribute to a downward spiral of divided politics, populism, and international dissonance.

Even prior to the COVID-19 outbreak, the geopolitical atmosphere was charged with international tensions, and there was a growing sense of societal frustration in developed and emerging market countries alike over economic and social imbalances. These sentiments are exacerbated in the early 2020s as many governments mishandle their domestic challenges, prioritizing the economy over health and social concerns. Rushed moves to rebound from the pandemic lead to renewed spikes in COVID-19 infections that severely damage public and market confidence, prolong the pandemic, and sustain the economic crisis.

Politicians are challenged with the conundrum of what to do next. Reactionary and populist sentiment grows. Already sharp political factions within countries become more divided and confrontational. Governments and leaders fall, with frequent ideological swings from left to right that result in a steady rise in authoritarian regimes. International relationships are similarly volatile. As international cooperation diminishes, geopolitical and economic tensions grow more severe. Security confrontations increasingly threaten to burst into open conflict.

In this sociopolitical environment, primary public interests and concerns are exclusively focused on health, economic recovery, and survival, and issues related to the environment move to the political sidelines. The combination of all these factors results in an extended period of economic malaise, political uncertainty, and policy weakness contributing to a deceleration of the transition toward a cleaner, lower-carbon energy future.

Efforts to address climate change and environmental degradation sputter under the weight of economic and political reality. While ongoing trends in clean energy technology advancements and market penetration continue, the progression is slowed by weaker supporting policies and market appetite and the extended use of incumbent energy sources, fuels, and infrastructure. By 2050, fossil fuels still account for almost three quarters of global primary energy demand, down from an 80% share in 2020. This result is compared with 64% for fossil fuels in the base case, Inflections. As a result, global GHG emissions in the Discord outlook rise throughout the scenario period from 48 billion metric tons of CO_2e in 2020 to 51 billion metric tons of CO_2e in 2050—a level that is 19% higher than in Inflections. In the Discord scenario, climate change efforts steadily turn from mitigation to adaptation.

Given the immensity of the political and economic challenges for many countries in 2021, the Discord scenario pathway is not surprising. The world flip-flops in and out of recovery, and vaccination programs falter as countries hoard supplies and constrain international aid. Borders remain tightly controlled, and global economic recovery stumbles. This situation results in an extended period of fear, economic malaise, and political uncertainty contributing to a troubled and fractured international landscape and a deceleration of the energy transition despite the hopes raised by the stream of net-zero GHG emissions targets announced by countries and companies in 2020 and 2021.

Key indicators for Discord

		History		Discord
		2019	2020	2050
Real GDP	Billion 2020 US$	87,417	84,150	163,498
	Average growth	2.9%	2.7%	2.2%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy consumption	MMtoe	14,590	13,798	16,417
	Average growth	1.8%	1.5%	0.6%
		(1990–2019)	(1990–2020)	(2020–50)
Primary energy intensity of GDP	Metric tons of oil equivalent per million 2020 US$	167	164	100
Primary energy shares	Oil	30%	30%	28%
	Gas	24%	25%	24%
	Coal	27%	21%	22%
	Nuclear	3%	3%	3%
	Hydro	5%	5%	5%
	Renewables*	3%	6%	6%
	Modern biomass**	5%	5%	5%
	Other***	5%	5%	7%
EV shares of LV market****	Sales	2.6%	4.4%	13.4%
	Fleet	0.5%	0.8%	7.6%
GHG emissions	Total ($MMtCO_2e$)****	50,740	48,066	50,633
	Energy-related ($MMtCO_2e$)	38,532	35,923	37,629
CO_2 emissions per GDP	Total ($MMtCO_2e$/US$ 2020)	580	571	310
	Energy-related ($MMtCO_2e$/US$ 2020)	441	427	230

Note: Some values have been rounded. MMt = million metric tons; MMtoe = million metric tons of oil equivalent; CO2e = CO2 equivalent; LV = light vehicle.

*Renewables include solar, wind, geothermal, and tide/wave/ocean energy.

**Modern biomass includes biofuels in transport and biomass used in industry, power generation, district heating, and refineries.

***Other includes solid waste, traditional biomass (used in the domestic sectors; includes charcoal, wood, bagasse), ambient heat, and net trade of electricity and heat.

****EVs is a comprehensive term that refers to all fully and partially electrified vehicles, including battery electric vehicles (BEVs), fuel-cell electric vehics (FCEVs), hybrid electric vehicles (HEVs), mild hybrid electric vehicles (MHEVs), and range extended electric vehicles (REEVs). However, the term is often applied just to battery electric vehicles.

*****Total GHG emissions represent global nonenergy-related CO2, methane, and nitrogen oxide (NOX) emissions combined with CO2 and methane emissions related to energy production and use. For consistency, nonenergy and methane emissions have been converted to CO2e amounts to provide a total figure.

Sources: S&P Global and the International Energy Agency (IEA) for history; S&P Global for outlooks

Detailed methodology by sector

Automotive

For the automotive sector, S&P Global conducted a bottom-up analysis of copper content in the components of different powertrains. The following powertrains were analyzed:

- Internal combustion engines vehicles (ICEVs)
- Battery electric vehicles (BEV)
- Hybrid electric vehicles (HEV)
- Plug-in hybrid electric vehicles (PHEV)
- Fuel-cell electric vehicles (FCEV)

Copper is present in both the harness of a vehicle, as well as in the electric motors (e-motors). Copper intensity estimates were developed for each component. For harnesses, estimates were made for three different price levels: entry, midrange, and premium cars to reflect the increased number of electronic features and varying degrees of copper wiring in high-end cars. For e-motors, the copper intensity of each type of motor was estimated. The figure provides a summary of copper intensity assumptions by component.

Copper intensity assumptions by component: Automotive

Harness	
Price class 1 (entry)	**10 kg/vehicle**
Price class 2 (mid)	**16 kg/vehicle**
Price class 3 (premium)	**22 kg/vehicle**

E-motor (EVs only)	
IPM and AFPM	**0.02–0.04 kg/kW**
IM, CEWRSM, CPSM	**0.16–0.17 kg/kWh**
SPM	**0.9 kg/kW**

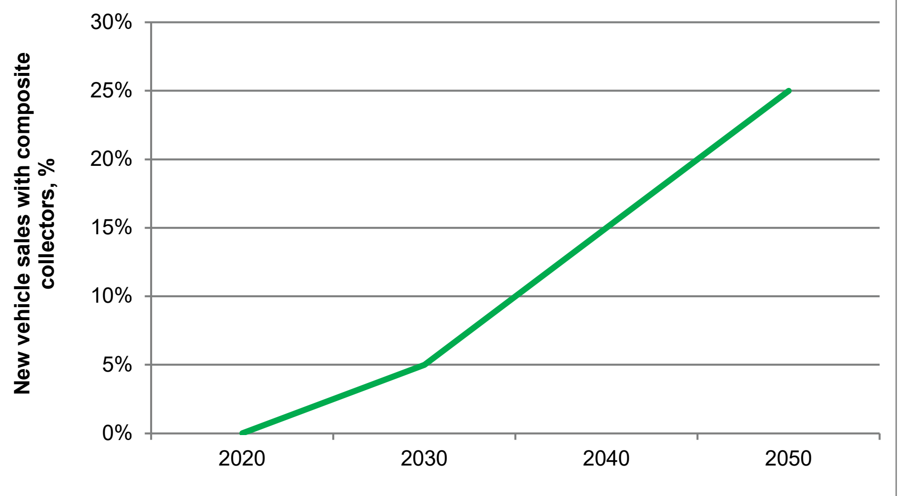
Note: Results are based on data available at the time of analysis, February 2022. IPM = interior permanent magnet; AFPM = axial flux permanent magnet; IM = induction motor; CEWRSM = current-excited wound rotor synchronous motor; CPSM = claw-pole synchronous motor; SPM = surface-mounted permanent magnet.

Source: S&P Global analysis, A2Mac1 Teardown data – harnesses and motors. © 2022 S&P Global: 2006288

Copper intensity for the battery pack was analyzed in the battery storage section.

In addition, potential copper intensity reduction was modeled based on technological evolution and efficiency improvements. In particular, composite adoption in collectors could lead to the replacement of a share of copper in batteries. The following figures show the outlook for copper reduction in collectors and harnesses.

Composite adoption in new vehicle sales



Note: Composite adoption results in 80% reduction of copper demand in collectors.
Source: S&P Global analysis

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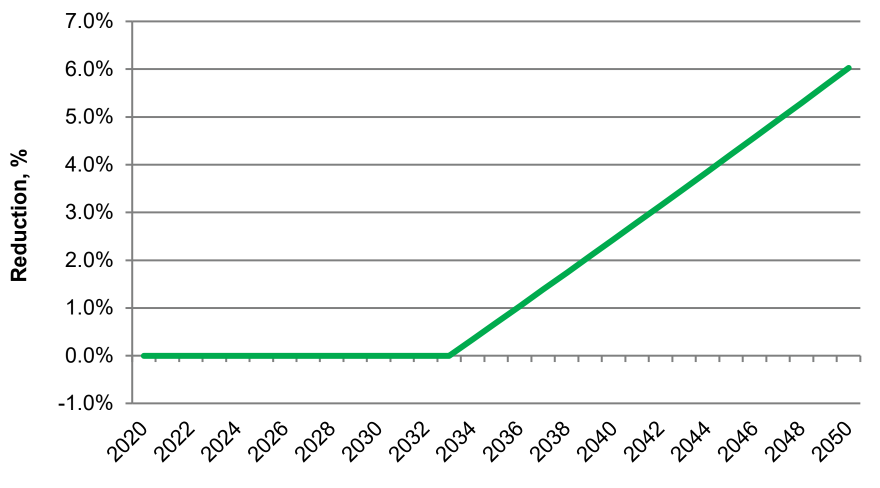
In harnesses, wire gauge will remain a barrier of substitution to aluminum. Aluminum cables require a larger cross-section for the same specifications, which poses an issue for vehicles. Composite adoption in new vehicles will have a larger impact as it results in a significant reduction of copper requirements in battery collectors. In this study, a 25% penetration of composite in collectors by the end of the period was assumed.

Overall copper intensity reduction in harnesses and e-motors



Note: 3.5% per 10 years after 2033.
Source: S&P Global analysis

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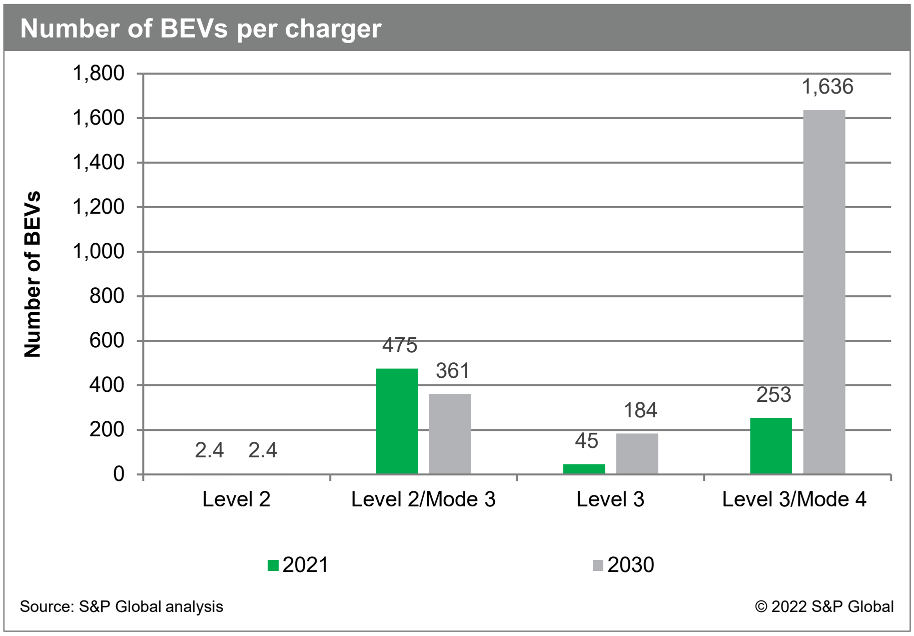
For EV chargers, copper intensity was estimated for the following different levels and modes of charger for current charger power:

- Level 2 and Mode 3: 1.05 kg/charger (7 kW)
- Level 3 and Mode 4: 4.48 kg/charger (80 kW) and 5.84 kg/charger (125 kW)

As technology evolves, charger power is expected to increase progressively, from 7 kW to 11 kW for Level 2 and Mode 3, and from 80 kW and 125 kW to 250 kW for Level 3 and Mode 4 chargers. As a result, copper intensity increases linearly.



Finally, charging infrastructure was forecast based on the BEV fleet outlook from the MTM scenario, with evolving assumptions on the number of BEVs per charger as illustrated in the figure below. As expected, as the number of BEVs on the road increases, high-voltage chargers are expected, on average, to serve a much larger number of vehicles. The exception is Level 2 chargers (mostly used in residential buildings), which will remain flat as most BEV owners are expected to set up their own charging infrastructure at home.

Power transmission and distribution

For power transmission and distribution, the projection of copper demand is based on required investments in transmission and distribution infrastructure in the MTM scenario. The copper intensity of the following subsegments was determined in this scenario:

- Transmission infrastructure (above 33 kV)
- Distribution infrastructure (below 33 kV)
- Transformers

As mentioned in *Chapter 3. Copper requirements in the energy transition* in the main report, copper is the material of choice in underground and subsea lines where technical characteristics play a larger role than weight. However, on the other hand, aluminum use is privileged for overhead lines in both transmission and distribution, and in particular for higher-voltage lines. As a result, the study assumes the use of copper for underground and subsea lines (in particular for offshore wind) and use of aluminum for overhead lines. Regional differences, however, do exist, in particular in China and Japan where copper is still widely used across transmission and distribution systems. However, these differences are expected to progressively disappear as building codes and regulations evolve.

For transmission and distribution lines, the average copper intensity in terms of kilograms of copper per kilometer and megawatts of line for different voltages was determined. The table below provides detail on the data points used to determine the copper intensity per type of line.

Transmission and distribution copper intensity by network type

Stage	Type	Relative Location	Power (MW)	Maximum rated voltage (kV)	Volume (kg/km)	Cross sec area (mm2)	Number of cables per circuit	Copper intensity (kg per km and MW)
Transmission								
	High voltage	Subsea	528	270	32,184	1,200	3	61
			337	220	21,456	800	3	64
	Medium voltage	Subsea	31	66	3,218	120	3	104
	High voltage	Underground	2,260	500	67,962	2,534	3	30
	High voltage	Underground	1,247	400	67,050	2,500	3	54
	Medium voltage	Underground	270	170	26,820	1,000	3	100
	Medium voltage	Underground	93	72.5	16,897	630	3	182
	Medium voltage	Underground	33	33	3,576	400	1	109
Distribution								
	Low voltage	Underground	14	20	6,437	240	3	475
	Low voltage	Underground	11	11	2,682	300	1	244
	Low voltage	Underground	5	6	3,218	120	3	611

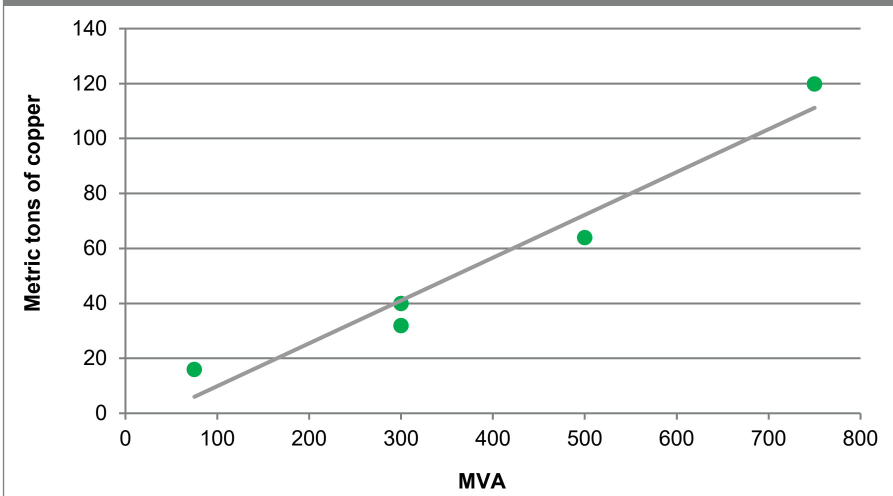
Note: Low voltage (LV) = up to 33 kV; medium voltage (MV) = 33 kV to 230 kV; high voltage (HV) = above 230 kV.

Source: S&P Global analysis, Primary and secondary research from major conductors manufacturers

For transformers, copper use was assumed to be dominant. Copper intensity and investments per megavolt-ampere (MVA) of capacity was estimated based on data from the US Department of Energy and various industry sources. The graph below provides key results.

From the copper intensity estimates described above, investments in transmission and distribution infrastructure were translated into overall length of new and replaced power lines by major country and region, as well as additional required transformer capacity to determine the resulting copper demand.

Three-phase transmission transformers weight and MVA rating correlation



Source: Primary and secondary research from major transfomer manufacturers

Solar PV

For solar PV, a bottom-up analysis of copper intensity per megawatt of installed capacity was conducted. Solar PV systems were broken down in the following subcomponents containing copper:

- PV cell tabbing and interconnection ribbon
- PV module cables and connectors (4-square-milimeter [mm2] cables)
- PV plant array cable (16 mm2 cables)
- PV plant field cable (50 mm2 cables)
- Inverters
- Step-up transformers

For each of these subcomponents, a range of existing academic literature, technical specifications from suppliers, and industry sources, as well as conversations with inverter suppliers and engineering, procurement, and construction (EPC) developers were relied upon to validate the findings. The figure provides a summary of copper intensity by component for current (2020) solar PV installations.

Copper intensity assumptions by component: Solar PV

PV cell tabbing and interconnection ribbon	**550 kg/MW**
PV module cables and connectors (4 mm^2)	**117 kg/MW**
PV plant array cable (16 mm^2)	**261 kg/MW**
PV plant field cable (50 mm^2)	**419 kg/MW**
Inverters	**70 kg/MW** (utility-scale) **450 kg/MW** (non-utility-scale)
Step-up transformers	**820 kg/MW** (average 2020) **1,320 kg/MW** (utility-scale)
Total (excl. transmission)	**2,290 kg/MW**

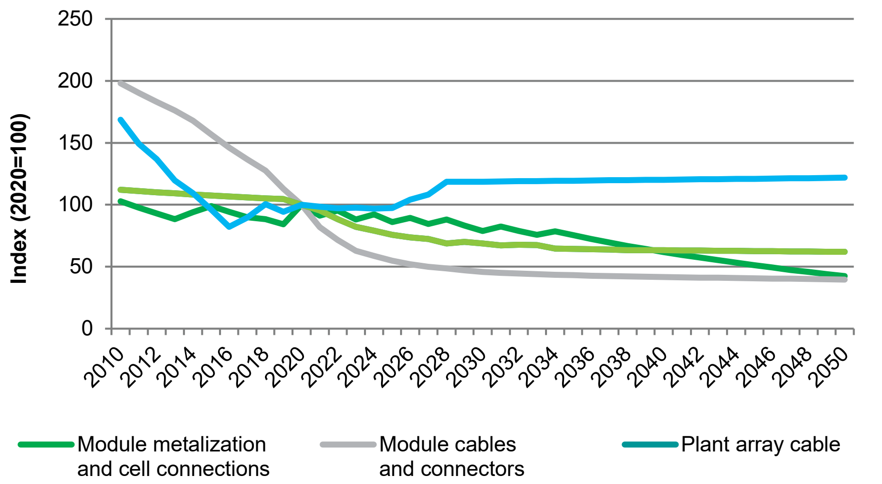
Note: Results are based on data available at the time of analysis, February 2022.

Source: S&P Global analysis, primary and secondary research including private conversations with inverter suppliers and engineering, procurement, and construction developers.

Based on the analyses and observed historical trends, continuous efficiency improvements (including substitution, when appropriate) were assumed for each of the modules. The decreasing amount for copper demand is mainly driven by technological improvements, such as increasing power (efficiency) per module, larger-size modules, and new designs of split junction boxes to the sides of the panel. In utility-scale solar PV installations, optimized systems using multiple panels in a string will require fewer wiring cables in the field. Increasing efficiency in panels with a rising share of N-type products and bifacial technology will offset increased copper usage in wires. The following figure provides the evolution of copper intensity for each component from the current baseline estimates.

Finally, copper intensity of inverters varies significantly between utility-scale and residential or commercial installations when estimated on an installed capacity basis. Utility-scale solar PV inverters are about 70 kg/MW as opposed to residential/commercial solar PV inverters at 450 kg/MW. The following chart provides an outlook of installed capacity by type.

Solar PV copper intensity efficiency improvement by component



Source: S&P Global analysis

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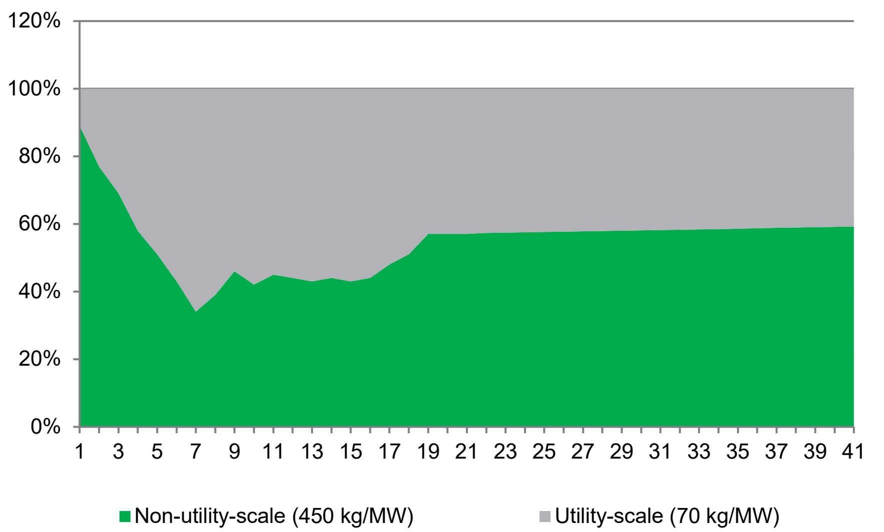
Solar PV installation types



Source: S&P Global

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Wind

For wind generation technologies, onshore and offshore wind have very different copper intensities, owing to the technologies used in the turbines, as well as the need for long transmission lines to shore for offshore wind.

For onshore wind, lifecycle assessments published by Vestas were relied upon[1]. The following table provides a summary of copper intensity for the selected lifecycle assessments of various onshore wind plants between 2015 and 2020.

Copper use across various turbines (Vestas reports)

				Copper requirements (per wind farm)									
Turbine size	Report date	Recycling rate	Wind farm size	Turbines	Foun-dations	Site cables	Switch-gears	Trans-former	Number of turbines	Total	Turbines only	Total without site cables	Site cables
MW		%	MW	tonnes	tonnes	tonnes	tonnes	tonnes		kg / MW	kg / MW	kg / MW	kg / turbine
2	Dec-15	92%	50	28	1	41	2	11	25	1660	560	840	1640
2	Dec-18	92%	50	49	1	41	2	11	25	2080	980	1260	1640
2	Dec-15	92%	50	30	1	41	2	11	25	1700	600	880	1640
3.3	Jun-14	92%	100	61	1	44	2	8	30	1160	610	720	1452
3.45	Jul-17	92%	100	92	1	43	2	8	29	1460	920	1030	1484
4.2	Nov-19	92%	100	83	1	40	2	8	24	1340	830	940	1680
4.2	Nov-19	92%	100	83	1	40	2	8	24	1340	830	940	1680
4.2	Nov-19	92%	100	89	1	40	2	8	24	1400	890	1000	1680
4.2	Mar-22	92%	100	89	1	40	2	8	24	1400	890	1000	1680

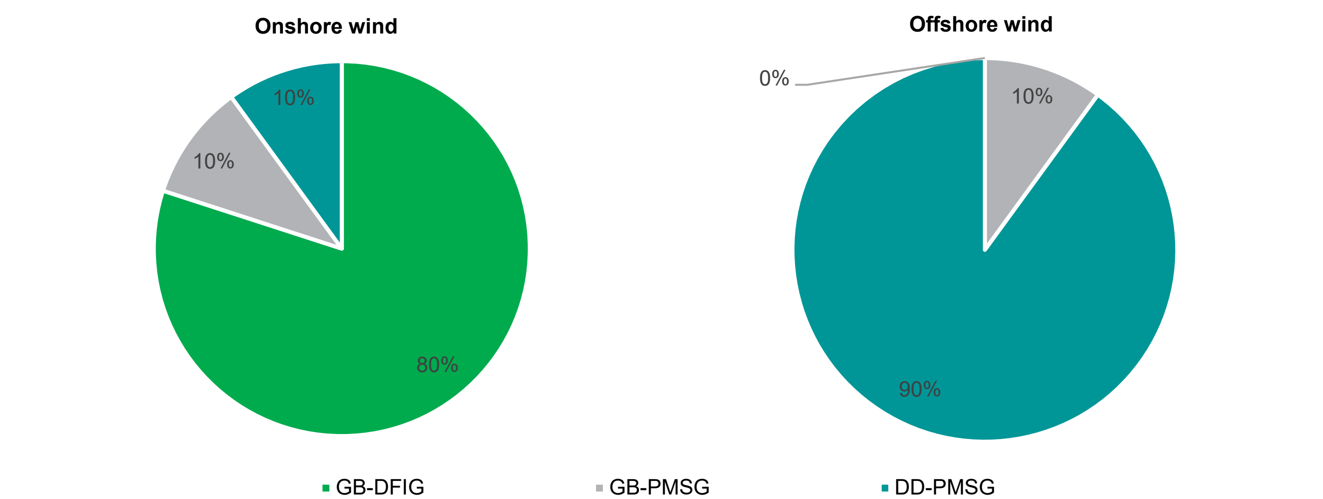
Source: Vestas Life Cycle Assessment of electricity production from an onshore wind plant (models: V112-3.3 MW, V105-3.3 MW, V117-3.45 MW, V117-4.2 MW, V136-4.2 MW, V150-4.2 MW), S&P Global analysis

Onshore wind relies mostly on doubly fed induction generators with a gearbox (GB-DFIG), with permanent magnet synchronous generators (PMSG) comprising only about 20% of capacity additions. Offshore wind, on the other hand, relies primarily on direct-drive (DD) PMSG turbines, which have a much higher copper intensity[2]. The following graphs provide an overview of capacity additions assumptions by turbine types:

1. Vestas Life Cycle Assessment of electricity production from an onshore wind plant (models: V112-3.3 MW, V105-3.3 MW, V117-3.45 MW, V117-4.2 MW, V136-4.2 MW, V150-4.2 MW).

2. European Commission, "Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system," 2020.

Wind turbine type distribution assumptions

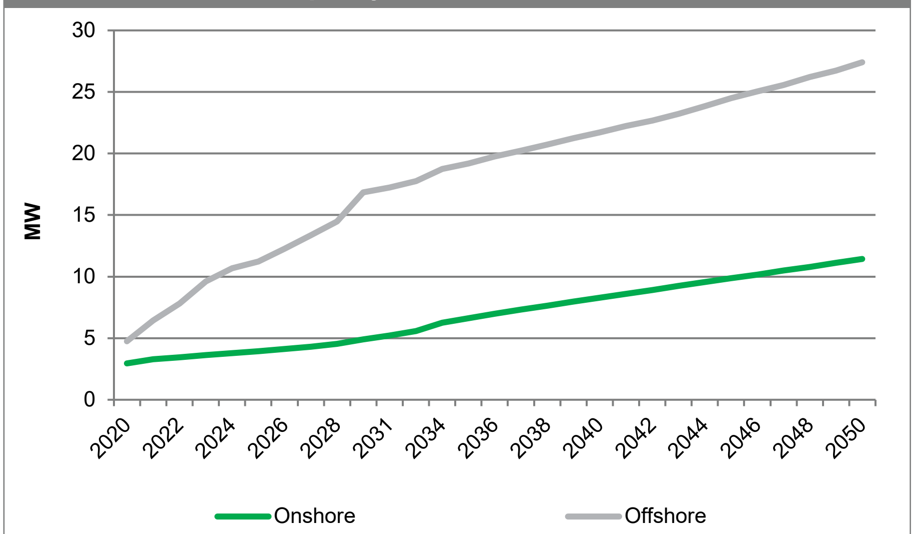


Note: GB-DFIG = doubly fed induction generators with a gearbox; GB-PMSG = permanent magnet synchronous generators with a gearbox; DD-PMSG = direct-drive permanent magnet synchronous generators.
Source: S&P Global analysis

In addition, turbine size has been steadily increasing with technological evolution. That trend is expected to continue with onshore turbine size going above 10 MW in the mid-2040s and offshore turbines reaching close to 30 MW. This turbine size increase will decrease copper intensity per megawatt of installed capacity.

As the best locations are progressively taken, offshore wind farms will be installed increasingly further from shore. The weighted average distance to shore is projected to increase from about 22 km in 2020 to 64 km in 2050 for bottom-fixed installations and from 50 km to 120 km for floating installations over the same period. Mechanically, this will increase the copper required for subsea transmission lines. The copper intensity of lines is estimated at approximately 44 kg/(km x MW).

Evolution of turbine capacity



Source: S&P Global

Battery storage

Copper intensity in battery storage technologies varies primarily based on the energy density of each technology. The key battery storage technologies currently in the market are

- Lithium-iron-phosphate batteries (LFP)
- Nickel-manganese-cobalt (NMC) 622 and 811
- Nickel-cobalt-aluminum oxides (NCA)
- Nickel-manganese-cobalt-aluminum (NMCA)
- Lithium-nickel-manganese oxide (LNMO)

Owing to a lower energy density, LFP batteries have the highest copper intensity per kilowatt-hour of capacity. The assumptions are derived from the Greet2 model developed by Argonne National Laboratories[3]. The graphic provides the underlying copper intensity assumptions for battery storage by technology.

Currently, NMC batteries are dominant in both the automotive and energy storage segments. We expect the battery technology mix to

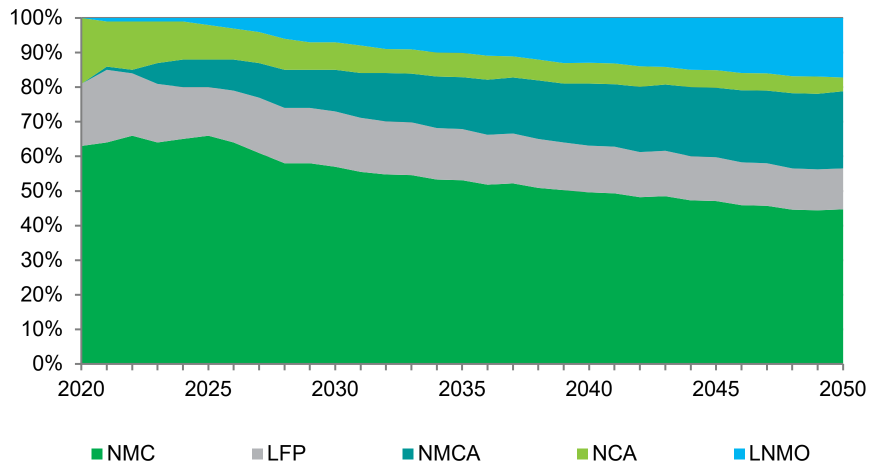
Copper intensity assumptions by technology: Battery storage

LFP	**1.05 kg/kWh**
LNMO	**1.00 kg/kWh**
NMC 622	**0.65 kg/kWh**
NMC 811	**0.64 kg/kWh**
NCA	**0.60 kg/kWh**

Notes: Results are based on data available at the time of analysis, February 2022. LFP = lithium-iron-phosphate batteries; NMC = nickel-manganese-cobalt 622 and 811; NCA = nickel-cobalt-aluminum oxides; LNMO = lithium-nickel-manganese oxide.

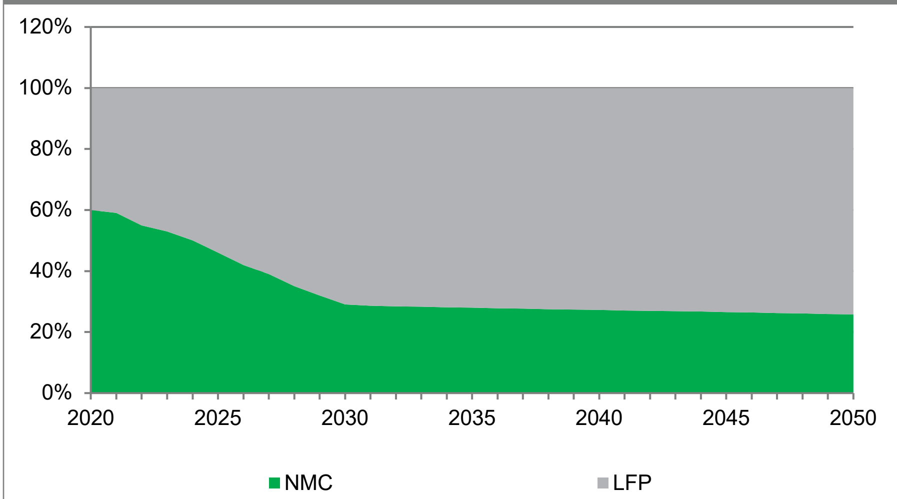
Source: Argonne National Labs, Greet2 model.

Battery capacity by technology in the automotive sector



Note: NMC = nickel-manganese-cobalt; LFP = lithium-iron-phosphate; NMCA = nickel-manganese-cobalt-aluminum; NCA = Nickel-cobalt-aluminum oxide; LNMO = lithium-nickel-manganese oxide.
Source: S&P Global

Battery capacity by technology in the power sector



Note: NMC = nickel-manganese-cobalt; LFP = lithium-iron-phosphate.
Source: S&P Global

3. The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET®) Model, Argonne National Laboratory, version 2021 rev. 1.

evolve as other technologies increase penetration. The graphs provide the outlook of various battery technology penetration between 2020 and 2050 for the automotive and power sectors.

Other technologies

For other renewable technologies with low projected installed capacity in the forecast, existing literature was relied upon. Average copper intensity values for pressurized water reactors, coal, natural gas, concentrated solar power (CSP), geothermal, biomass, and tidal technologies were derived from *Materials for Low-Carbon Power – A white paper*, Ashby, Attwood, Lord (2012).

As a comparison, the cumulative capacity additions from CSP, geothermal, biomass, and tidal technologies represent 1.6% of the total cumulative capacity additions between 2021 and 2050. On the other hand, cumulative capacity additions from solar PV, onshore/offshore wind, and battery storage represent 87% of total capacity additions over the same period.

Nonenergy transition demand and supply

Forecasts for both nonenergy transition demand and supply for refined copper were developed at the country level using historical data from the International Copper Study Group (ICSG) back to 1994, the earliest year in the data set.

Demand analysis

Total refined copper demand was estimated by combining forecasts of energy transition demand, whose methodology is detailed in the section above, with estimates of nonenergy transition copper demand. These estimates were then reconciled to form total copper demand estimates.

Nonenergy transition usage

Nonenergy transition copper demand was analyzed using data from S&P Global's Comparative Industry Service (CIS), which forecasts market sizes by country and industry. The US Geological Survey's 2021 Mineral Commodity Summary estimates the end market's share of copper usage as noted in the table.

Usage of copper by end market

Category	Percentage of total
Building construction	43%
Electrical and electronic products	21%
Transportation equipment	19%
Consumer and general products	10%
Industrial machinery and equipment	7%

Note: 2021 US Geological Survey Mineral Commodity Summary, Copper

Source: S&P Global, US Geological Survey

Each of the end markets above were mapped to an industry in CIS. Demand for each country was then estimated using the growth of each industry's market size and weighted using the end market shares from the figure above.

Energy transition usage

The methodology for energy transition copper demand is described in detail in the above Energy transition demand section, which provides estimates on the copper intensity in key energy transition technologies and the resulting copper demand for energy transition technologies.

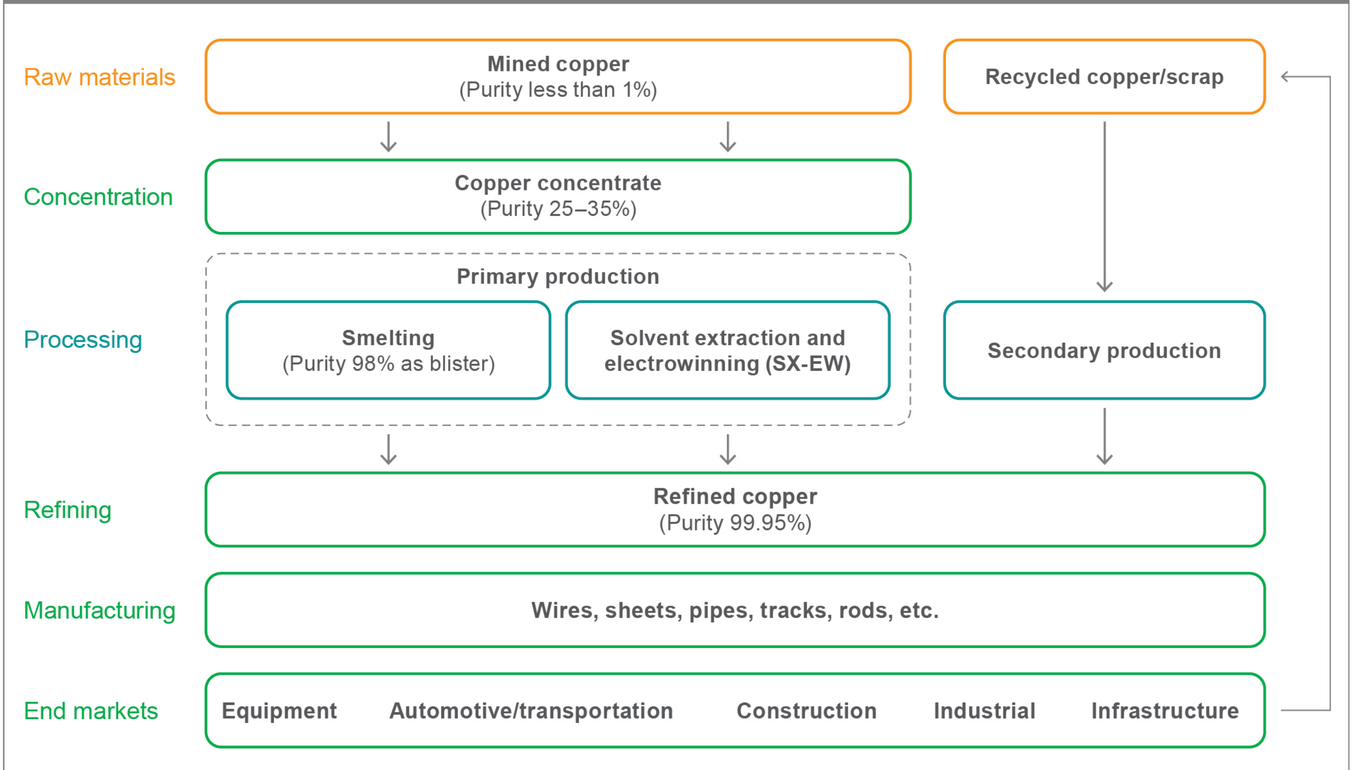
Because nonenergy transition copper demand was analyzed using annual data at the country level and there has been some energy transition copper usage in 2021 and earlier, some energy transition usage was included in the initial nonenergy transition usage estimates, namely in the automotive, transmission and distribution, and power technologies. S&P Global's Discord scenario was used to estimate how much energy transition demand was included in these estimates and reconcile these two sets of demand estimates.

The Discord scenario assumes that there is a breakdown in efforts toward an energy transition. In this scenario, copper usage in energy transition end markets does increase, though at a far lower growth rate than the MTM scenario. Because demand under the Discord scenario was already included in the nonenergy transition demand forecasts, the difference between copper demand in the MTM scenario and the Discord scenario for each of these energy transition technologies was added to the nonenergy transition demand forecasts to form total copper demand.

Supply analysis

There are two ways to refine copper: through refining mined copper or refining scrap or recycled copper. Primary production, or the production of primary refined copper, is the refining of mined copper. Meanwhile, secondary production is the refining of copper scrap or recycled copper.

Copper: From mining to market



Note: End markets listed are not exhaustive.
Source: International Copper Study Group (ICSG)

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Using this production flow, primary and secondary production were first analyzed with the sum of both being total refined copper production.

Primary production

Because primary production is the refining of mined copper, mined copper production was derived by multiplying mined capacity by capacity utilization.

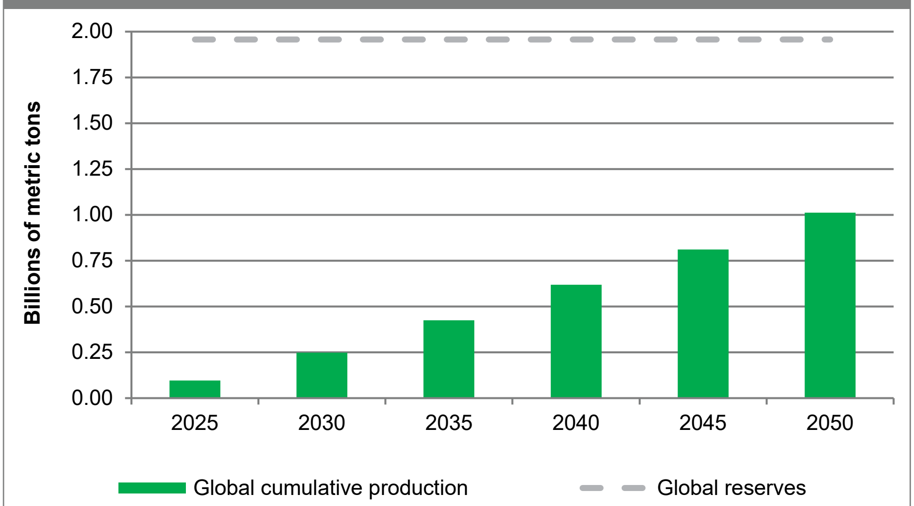
Mined capacity

The analysis of mined capacity was done in two parts: the short term and long term. The short-term outlook for mined capacity used the ICSG Directory of Mines and Plants, which is a database of all copper mines in the world with estimates of annual capacity in metric tons at the individual mine level over the next four years. Capacity at the mine level was aggregated to the country level for each year, forming capacity forecasts through 2026.

The long-term outlook past 2026 was developed using drivers from the S&P Global CIS Mining of Metal and Stone production forecasts by country. CIS uses an approach to production forecasts that leverages input-output techniques to derive estimates of output by industry, where the requirements of all the downstream industries such as the refined nonferrous metal products, construction, and other industries drive mining production. In addition, country risk assumptions and, more importantly, commodity market expertise were imbedded to arrive at the industry outlook. Additionally, after developing the set of initial forecasts, industry experts revised the outlook by utilizing expert judgement, additional data, and resources such as the US Geological Survey's reserves and resource base estimates.

Another option for forecasting long-term mine capacity is using a bottom-up, mine-by-mine approach. This approach was not utilized in this analysis for two main reasons. First, there are several politically sensitive mining projects in development or under environmental review. The modeling approach avoids making strict assumptions on when or whether these developments would enter production. Second, the long-term econometric approach considers the interplay of country risk factors, industry, and macroeconomic forecasts yielding a cohesive forecast.

Global cumulative mined production 2025–50 compared with global reserve estimates



Source: USGS, S&P Global

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Capacity utilization

Capacity utilization assumptions were made at the country level for each year and were informed by historical capacity utilization data provided by the ICSG in two ways. First, by using each country's peak and average capacity utilization in the 1994–2021 sample period, and second by how long utilization can be sustained at high levels, above 95%. These provided guidelines for the assumptions of the level capacity utilization can reasonably reach in the forecast period and how long capacity utilization can stay at high levels.

While capacity utilization measures are largely a function of disruptions and maintenance rather than a conscious decision by miners to produce, there is a relationship between capacity utilization and price. When prices are high, there is a strong incentive to resolve issues that would cause production disruptions and delay maintenance, given the high opportunity cost.

Under the High Ambition scenario, capacity utilization is expected to generally increase through 2035 in line with the ramp-up in energy transition copper demand, which will tighten the market and increase prices. On a global level, capacity utilization is expected to peak at roughly 96% in 2035, just above the global high of 93.4% in 1997. While most countries are not expected to reach their peak capacity utilization rate during the outlook, assumed capacity utilization rates on a global level will at times exceed the global peak of 93.4%. This is because there will be years where most countries have high capacity utilization assumptions, increasing the overall global rate to above its historical peak.

Under the Rocky Road scenario, the global capacity utilization rate is held constant from 2022 to 2050 at 84.1%, the average global rate between 2012 and 2021.

Refining of mined copper

Because mined copper is often refined in a different country than it is mined, additional steps must be taken to estimate primary production by country. Since there is a steady relationship between mined production and primary production on the global level, global primary production was assumed to be 97.8% of global mined copper production, which is the average ratio between the two measures during our 1994 to 2021 sample period.

Global primary production was then distributed down to the country level using CIS estimates for the production of nonferrous metals products by country, where the country primary production estimates were then constrained to the global total.

Secondary production

Secondary production, or the refining of recycled copper or copper scrap, was estimated in two steps: recycling of traditional copper end markets and incremental recycling from energy transition demand.

Recycling of traditional (nonenergy transition) end markets was estimated in two steps, first at the global level and then by country. The first step was an assumption of the future trend of global secondary production as a percentage of total refined production based on expert judgment.

Once recycling rates on a global basis were established, secondary production for traditional copper end markets was then shared down to the country level using the CIS estimates for the production of nonferrous metals products by country, and then constrained to the global total.

Under the High Ambition scenario, recycling rates increase through 2035. Between strong demand fostering a tight market, high prices, and evolving environmental regulations that mandate to increase recycling rates in key industries, there will be strong incentives for recycling rates to increase through 2035. Thereafter, the emerging surplus expected to begin in 2040 will drive a modest draw-down in recycling rates.

In the High Ambition scenario, incremental secondary production from energy transition end markets was estimated by assuming an asset lifespan and recycling rate for each technology. Because public policy will likely mandate a higher level of recycling, recycle rates were assumed to increase over time. For example, a lifespan of 18 years was assumed for the automotive sector, with its recycle rate rising from 85% in 2020 to 95% in 2050. That means recycling from automobiles in 2050 is 95% of the copper consumed in automobiles 18 years prior.

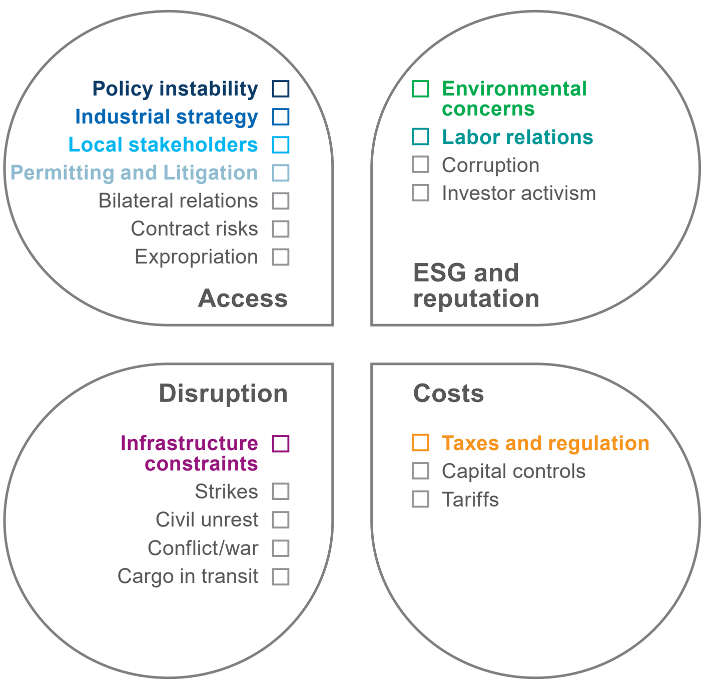
Under the Rocky Road scenario, global recycling rates, or secondary production as a percentage of total refined production, is held constant throughout the outlook at 17.0%, the average global rate between 2012 and 2021.

Operational challenges

Capturing operational challenges in copper sourcing countries

Whereas the demand and supply analysis of this report are built on quantified projections, operational risks are irreducibly qualitative and local. Understanding them requires individual country expertise. But to render insights comparable, they must be captured in a standardized way. To this end, structured discussions were conducted with the S&P Global Country Risk team's relevant network of in-country sources and contributors. The interviews focused on four areas critical to operations that are shown below.

Four areas of focus



Source: S&P Global Country Risk

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Country experts were asked to describe these risks and their relevance to the copper industry in their countries. Their insights are their own but draw upon in-country and sector-specific sources and contributors. Typed notes from interviews were returned to country experts to allow revisions for accuracy.

The consistent approach reveals divergent issues among the key sourcing countries—but within four consistent frames of reference. Interviews were efficient and productive because these frames of reference are well known to our team as part of a globally consistent methodology. The approach has been built on long-established daily workflows in the Country Risk team, drawing on an in-country source and contributor networks and calibration of risk assessments by a team of experienced, senior analysts. Our country experts, recruited for intimate knowledge of specific countries and/or industrial sectors, interpret the intelligence from open and human sources to form analytical assessment and forecasts. The core team is supported by more than 200 country analysts spread around the world and a network of more than 800 human sources for expert inputs. A separate “audit” team of senior subject matter experts review and challenge all analysis to ensure it is rigorous, relevant, and globally consistent.

Appendix C. Glossary

Alloy. A substance with metallic properties composed of two or more chemical elements, at least one of which is metal, typically to increase strength or improve corrosion resistance. Copper alloys include bronze (copper and tin) and brass (copper and zinc).

Anode. The negatively charged electrode in an electrochemical battery.

Battery electric vehicle (BEV). Fully electrified vehicles, powered solely by batteries.

Billet. A solid or hollow cast form, usually cylindrical, suitable for extruding.

Brass. An alloy that is composed of copper and zinc. The zinc content in brass is generally between 28% and 33%. Any higher and it begins to lose the advantages of strength and ductility found in the alloy.

Bronze. An alloy of copper and tin.

Cathode. The positively charged electrode in an electrochemical battery.

Class (truck). Categorization of trucks by gross vehicle weight (GVW). 'Class 4–5' refers to trucks with GVWs between 14,001 pounds and 19,500 pounds (6.4–8.8 metric tons); 'class 6-7' refers to trucks with GVWs between 19,501 pounds and 33,000 pounds (8.8–15.0 metric tons); 'class 8' represents all vehicles with GVWs exceeding 33,000 pounds.

Concentrate. A product containing valuable minerals from which most of the waste material in an ore has been removed. Concentrates are an input for smelting or leaching.

Copper. A red-brown metallic chemical element with atomic number 29 on the periodic table. Pure copper is rarely found in nature but is usually combined with other chemicals in the form of copper ores. There are about 15 copper ores mined commercially in 40 countries around the world. The most common are known as sulfide ores, in which copper is chemically bonded with sulfur. Others are known as oxide ores, carbonate ores, or mixed ores depending on the chemicals present. Many copper ores also contain significant quantities of gold, silver, nickel, and other valuable metals, as well as large quantities of commercially useless material. Most of the copper ores mined in the United States contain only about 1.2–1.6% copper by weight.

Current collector. This collects the electrons that are generated from the battery's electrochemical reaction. Cathode current collectors are typically composed of aluminum; anode current collectors are typically composed of copper.

Direct-drive turbines (DD). A wind turbine design that eliminates the need for a gearbox. A direct-drive wind turbine's generator speed is equivalent to the rotor speed, because the rotor is connected directly to the generator.

Doubly-fed induction generator (DFIG). A popular system in wind turbines where the power electronic interface controls the rotor currents to achieve the variable speed necessary for maximum energy capture in variable winds.

Electric vehicle (EV). A comprehensive term that refers to all fully and partially electrified vehicles, including BEVs, FCEVs, HEVs, mild hybrid electric vehicles (MHEVs), and range-extended electric vehicles (REEVs). However, the term is often applied just to battery electric vehicles.

Electrification. The process of replacing technologies that use fossil fuels (coal, oil, and natural gas) with technologies that use electricity as a source of energy.

e-motor (vehicle). An electrical machine that converts electrical energy into mechanical energy. An electric generator is mechanically identical to an electric motor, but operates with a reversed flow of power, converting mechanical energy into electrical energy.

Energy transition. The global energy sector's shift from fossil-based systems of energy production and consumption—including oil, natural gas, and coal—to renewable energy sources like wind and solar, as well as Li-ion batteries.

Fuel-cell electric vehicle (FCEV). A fully electrified vehicle that is primarily powered by a fuel cell. All FCEVs also require small Li-ion batteries.

Gearbox turbines (GB). A turbine with a gearbox between the low-speed rotor and a higher-speed electrical generator (usually a relatively standard DFIG), the purpose of which is to increase the rotational rotor speed before feeding it to the generator. For this wind-turbine type, the blades rotate by a shaft connected via the gearbox to the generator.

Harness (vehicle). The complete electrical wiring system of a vehicle.

Heavy-duty vehicles. Vehicles with a GVW above 33,000 pounds or 15.0 metric tons (class 8 vehicles).

Hybrid electric vehicle (HEV). A vehicle that uses a combination of an ICE and an electric motor (typically powered by a battery) for motive force, where the electric drivetrain is capable of powering the vehicle alone.

ICSG. International Copper Study Group.

IEA. International Energy Agency.

IMF. International Monetary Fund.

Ingot. A cast form suitable for remelting or fabricating.

Internal combustion engine (ICE). A conventional automotive engine powered by petrol/gasoline or diesel.

Inverter. A power electronic device or circuitry that changes direct current (DC) to alternating current (AC). The resulting AC frequency obtained depends on the particular device employed. Also known as a power inverter or invertor.

Light-duty vehicles. Vehicles with GVWs of less than 14,000 pounds or 6.4 metric tons (class 1–3 vehicles), typically motor cars, vans, and pick-up trucks.

Lithium cobalt oxide (LCO). Lithium cobalt oxide is one of the most common Lithium-ions batteries. LiCoO2 is its chemical symbol and is abbreviated as LCO. Cobalt is the core active material and defines the characteristics of the battery.

Lithium-iron-phosphate (LFP). A cathode material with high thermal stability and high-power capability, but low energy density. LFP (LiFePO4) cathodes are most commonly used in electric buses and energy-storage systems.

Lithium-nickel-manganese oxide (LNMO). A cathode material that can be charged at high voltage (5V). Lithium-manganese-nickel oxide (LiMn1.5Ni0.5O4) cathodes have a higher energy density compared with LCO and LFP. LNMO-based batteries can be used in high-energy and high-rate applications.

Medium-duty vehicles. Vehicles (trucks) generally with GVWs of 14,001–19,500 pounds or 6.4–15.0 metric tons (class 4–7 vehicles).

Metric ton (mt). 1,000 kilograms or 2204.6 pounds.

MMt. Million metric tons.

MTM. The S&P Global Multitech Mitigation scenario.

Net-zero emission. The point when greenhouse gases that are released into the atmosphere and those displaced from it balance, i.e., cancel out each other.

Nickel-cobalt-aluminum (NCA). NCA (LiNi0.8Co0.15Al0.05O2) cathodes have high usable discharge capacity and a long storage calendar life.

Nickel-manganese-cobalt (NMC). NMC (LiNixCoyMnzO2) cathodes achieve similar specific capacity and operating voltage to LCO, but at a lower cost and improved thermal stability. There are a variety of NMC formulations in which the numbers following the letters indicate the corresponding ratios. For example, NMC-111 has a 1:1:1 ratio of nickel to manganese to cobalt, whereas NMC-811 is a high-nickel variation with an 8:1:1 ratio of nickel to manganese to cobalt. All NMC formulations are used in BEVs, but only low-nickel variations are used in energy storage.

Nickel-manganese-cobalt-aluminum (NMCA). NMCA batteries are a combination of NMC lithium batteries and aluminum. The portion of nickel is 89–90% with cobalt accounting for less than 5%. Recently, battery manufacturers are focusing on 'high nickel' to extend electric vehicles' driving distances. The higher the nickel content, the higher the battery's energy density and capacity. Aluminum is introduced to improve chemical stability and improve output.

Nonenergy transition markets. Traditional copper end markets not related to the energy transition, such as building construction and consumer products.

Ore grades. The concentration of an element of interest in a potentially mineable ore deposit. The higher the concentration of the element, the higher the quality of the ore.

Permanent magnet synchronous generator (PMSG). A generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous here refers to the rotor and magnetic field rotating with the same speed.

Plug-in hybrid electric vehicle (PHEV). A vehicle using both an ICE and an electric motor powered by a battery for motive force. The electric drivetrain is capable of powering the vehicle alone and the battery can be charged from an external source.

Primary copper production. A set of multiple processes required to extract copper ores and convert it to refined copper.

Refinery. A plant where concentrates or matte are processed into one (or more) refined metals.

Secondary copper production. The recovery and recycling of copper for reuse.

Smelt. To fuse or melt ore in order to refine or extract metal.

Smelter. A plant where concentrates are processed into an upgraded product.

Solar photovoltaic (PV). Technologies that convert sunlight into electrical energy through photovoltaic (PV) panels.

Solvent extraction and electrowinning (SX-EW). Solvent extraction-electrowon copper production; an alternative method of producing near–refinery grade (or refinery grade) copper, which is suitable for certain types of copper ores (i.e., oxide ores). The advantage of SX-EW production is that it is generally much lower in cost compared with traditional smelter-refinery cathode production.

T&D. Transmission and distribution infrastructure is the backbone of the electric power system as it facilitates the delivery of electricity from power plants to end customers.

Transformer. A passive component that transfers electrical energy from one electrical circuit to another circuit, typically at either stepped-up (higher) voltages or stepped-down (lower) voltages.

Wind energy. Energy that utilizes the kinetic energy of moving air through wind turbines located on land (onshore) or in seawater or freshwater (offshore).

Zero-emission vehicle (ZEV). A vehicle that does not produce any significant emission (at the tailpipe).

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