THE COPPER TUTORIAL

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COPPER ALLIANCE

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Updates for this edition

- Section 3.5 added.
- Section 3.6 added.
- Minor update of section 5.3 – references.
- Section 8.1. added.
- Minor update of section 9.2 – link added for safety benefit.
- Minor edit to section 10.1.
- Expansion of section 10.3 with flow diagram.
- Minor update for section 12.1 – references.
- Expansion of section 18.3 – list extended.
- Update of section 20.1 – annual report added.
- Update of section 20.7.3 – 2023 report on materials movement added.
- Minor update to section 21.1 – CDA glossaries added.

Disclaimer

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0. About the tutorial

0.1. Acknowledgement

A warm thanks to my colleagues from the copper network and its members and partners who have been extensively contacted to provide generous input on the complex story of copper:

In alphabetical order, and without committing any contributor to the content: Florian Anderhuber (Euromines), Stijn Baken, Colin Bennett, Mukund Bhagwat, Laurent Chokoualé Datou, John Fennell (ICAA), Efren Franco, John Hipchen, Andy Kireta, Marcel Kloska (Aurubis), Steve Kukoda, Katia Lacasse, Richard Leveille, Mark Loveitt (IWCC), Amelia Miles, Fernando Nuno, Víctor Pérez (Alta Ley), Gabrielle Peterson, Robert Pinter, Michal Ramczykowski, Ana Rebelo (ICSG), Bernard Respaut, Carlos Risopatron (ICSG), Geraud Servin, Hernan Sierralta, Aleksandra Szkutnik-Wolszczak (KGHM), Luis Tercero (Fraunhofer), Ladji Tikana (Kupferverband), Wendy Wellens, Tanja Winter (Aurubis)

Last update: December 9, 2022

0.2. The making of the copper tutorial

Through this initiative, the Copper Alliance (CA) aims to answer a central question: how can the central role that copper plays in the energy transition, the circular economy and digitalisation be balanced with the potential environmental and social impacts of copper production?

The copper tutorial aims to provide a full picture of copper, from mining to end-of-life and recycling. It’s a complex story. Copper, as a base metal, is ubiquitous. If a system doesn’t directly use copper, copper has often played a role in its production. Copper makes applications more efficient, reliable and safe. Once mined, copper has a long lifetime of use. As it is one of the few metals that can be recycled without loss of properties, it not only has a long lifetime, but it also can have many lives.

To release these benefits, we need mining and recycling, i.e., primary and secondary raw materials. Gradually, as the world economy develops, the share of secondary raw materials can increase. But, there remains a need for mining to support societal growth, to provide copper for the green transition and to compensate for losses in an increasingly circular economy. Currently, there are close to 500 working copper mines, ranging from small operations to the world’s largest copper mines, such as Escondida, Grasberg or Morenci. How many mines are needed, and how can these mines be justified from an environmental or social perspective?

The copper tutorial is based on published materials. There is a rich literature on copper, and therefore, CA does not need to reinvent the wheel and can follow a curation approach. The tutorial provides short answers to frequently asked questions with links to further information.

While the copper industry is ever-changing, and new data and research is continually in development, CA experts work to provide information that is accurate and up-to-date. The tutorial answers are open for comments, and CA welcomes the viewpoints of those interested in the copper industry.

The copper tutorial is available at http://help.copper.fyi. Through an artificially-intelligent system, users can ask questions about copper. If an unanswered question remains, please type it in the search box, and an additional answer will be developed if it is available.

Welcome to the copper tutorial!

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Last update: 3 June 2022

1. History of copper

1.1. How long has copper been used by mankind?

> “The story of copper and its principle alloys, bronze and brass, is virtually a chronicle of human endeavour since man emerged from the Stone Age.[Webster Smith in “Sixty Centuries of Copper” (1965 edition)]”

Copper was the first metal used in quantity by humans. Since 10,000 BC, 12 millennia ago, copper helped to pull mankind out of the Stone Age. Initially, native copper was used to exploit copper’s corrosion resistance, good workability and high thermal conductivity.

Around six millennia ago, humans mastered the skill to extract copper from ore and went on to alloy copper into bronze for improved strength and durability.

More information

- 60 centuries of copper: a microsite based on Webster Smith’s book freely available from the CDA Inc website - https://www.copper.org/education/history/60centuries/
- Copper timeline: an interactive resource from CDA Inc, providing copper milestones against the context of human development - https://www.copper.org/education/history/timeline/

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Last update: Monday, 30 June 2022

1.2. Where can I find copper on Unesco's World Heritage List?

A search on 'copper' produces 14 results on the World Heritage List. Of these, some entries have rather cursory linkages to copper, leaving ten heritage sites where copper is present on the central stage:

1. Chile: Sewell - Mining town.
2. Germany: Rammelsberg - Non-ferrous metal mining;
3. Germany: Bremen - Copper roof
4. Germany: Wilhelmshöhe - Copper statue of Hercules
5. Jordan: Petr - Umm al Amad copper mines and underground galleries (fourth millennium BC)
6. Norway: Røros - Mining town
7. Oman: Archaeological Sites of Bat, Al-Khutm and Al-Ayn - copper extraction (third millennium BC)
8. Sweden: Falun - copper mining since the 13th century
9. Tajikistan: Sarazm - copper working
10. UK: Cornwall - 56 copper mining sites, producing 50% of world copper in the 19th century
11. US: New York - Statue of Liberty

Last update: March 1, 2022

1.3. What are some of the oldest copper companies (that still operate today)?

If we include precursors, some copper companies have roots back to the 16th century, but most companies started in the 19th and 20th centuries with the industrial revolution. Hereby an incomplete overview.

Copper Alliance Members

Company	Start Year (precursors)	Activity	Link
Anglo American	1917	Mining	>>
Antofagasta	1888 (1980 - mining)	Mining	>>
Aurubis	1876 (1770)	Smelting & refining	>>
BHP	1885 (1851)	Mining	>>
Boliden	1920	Mining	>>
Codelco	1976 (1955)	Mining	>>
Collahuasi	1880	Mining	>>
Freeport	1988 (1834)	Mining	>>
Glencore	1974	Mining	>>
Grupo Mexico	1892	Mining	>>
KGHM	1949	Mining	>>
LS Nikko	1936	Smelter	>>
Mitsubishi Materials	1871	Mining	>>
Outotec	~ 1850	Technology	>>
Rio Tinto	1873	Mining	>>
Southern Copper	1952	Mining	>>
Sumitomo Metal Mining	1590	Mining	>>
Teck	1913 (1954 - Cu)	Mining	>>
Vale	1901	Mining	>>

Other actors

Company	**Start Year (precursors)**	**Activity**	**Link**
Chinalco Luoyang	1954	Fabricator	>>
Furukawa	1896	Wire & cable	>>
Griset	1760	Fabrication	>>
KME	1886	Fabrication	>>
Leoni	1917 (1569)	Wire systems	>>
Materion	1931	Advanced materials	>>
Nexans	1897	Wire & cable	>>
Prysmian	1879	Wire & cable	>>
Sims Ltd	1917	Recycling	>>
Wieland	1820	Fabrication	>>

Since copper is a very long-term business, it matters that mining operators can manage a project through its entire life-cycle. The median start date of operations for Copper Alliance's membership is 1907. Our youngest member started in 1988 while the oldest member has roots going back to the 16th century.

Last update: November 25, 2021

2. Copper's properties

2.1. How does copper set the standard for electrical conductivity?

As the best electrical conductor among metals, 70% of copper is used for conductivity applications. So how does copper set the standard for conductivity?

In 1913 (revised in 1925), the International Electrotechnical Commission (IEC) adopted the German standard for the electrical conductivity of copper. This International Annealed Copper Standard (IACS) has become the main reference for electrical conductivity, and the conductivity of copper and aluminium alloys are usually expressed in terms of IACS.

The IACS standard describes the properties for 100% IACS at 20°C:

- Volume resistivity: 1/58 = 0.017241 ohm-mm2/m
- Temperature coefficient of volume resistivity = 68e-6 ohm-mm2/m.K
- Density: 8,890 kg/m3
- Mass resistivity: 0.15328 ohm-gramme/m2
- Temperature coefficient of mass resistivity = 0.00393/K

Since the adoption of IEC 60028, copper processing technologies have improved and, as a result, routine production of high-conductivity copper can reach or exceed 101% IACS.

The conductivity of other metals can be expressed in IACS as well:

Metal	**IACS**
Silver	106%
Copper	100%
Gold	70%
Aluminium (unalloyed)	61%
Iron	17%
Lead	8%
Stainless steel	2%

References

- IEC 60028:1925 - International standard of resistance for copper, available from https://webstore.iec.ch/publication/98 (checked October 28, 2021)
- White paper, electrical conductors, European Copper Institute, June 2019

Last update: June 1, 2022

2.2. How does copper compare to aluminium as a conductor for electricity?

Copper and aluminium are both extensively used as electrical conductors. How to compare a copper and an aluminium conductor? Cf the table below:

- Copper sets the standard for conductivity. Aluminium has about 60% of copper's conductivity, or copper is about 66% more conductive for electricity.
- Aluminium is 3.3 times lighter than copper.
- Hence, for the same current carrying capacity and the same efficiency (in ohmic regime):
  - The copper conductor will be 3.3/1.66 = 2 times heavier.
  - An equivalent aluminium conductor will be 1.66 larger in cross session, hence have 1.29 times the diameter., requiring more insulation, more steel, more oil, ... Or the copper conductor can save 22% (= 0.29/1.29) on materials surrounding the conductor.

Parameter	**Unit**	**Copper**	**Aluminium**
Conductivity	% IACS	101	61
Relative conductor cross section	-	100	166
Density	kg/l	8.9	2.7
Equivalent weight for the same current capacity	kg	1	0.5

In practice, conductor diameters are rarely available in 66% diameter increments and small differences in cable efficiency will be observed when comparing a copper conductor with a 1-size-up aluminium conductor. In addition, for power cables, other factors such as eddy currents and the proximity effect define a cable's efficiency. As for electrical machines such as motors and transformers, energy efficiency varies as a function of other design parameters besides conductor cross section.

Therefore, typical material savings in the range of 8-25% can be expected from the benefit of copper's compactness:

- Insulated cables: savings on the amount of insulation materials between 10 and 25%.
- Distribution transformers: 8-12% savings in steel when replacing the high-voltage winding with copper.
- Induction motors: 8-13% savings in steel when using a copper rotor induction motor.

References

- IEC 60228, Conductors of insulated cables
- Preparatory study for the review of Commission Regulation 548/2014 on ecodesign requirements for small, medium and large power transformers, July 2017, https://transformers.vito.be/sites/transformers.vito.be/files/attachments/ec_dg_growth_lot2_Transformer_Jul2017b.pdf - accessed June 23, 2022
- Francesco Parasiliti, Marco Villani, New induction motor designs with Aluminum and Copper rotor specially developed to reach the IE3 efficiency level, University of L'Aquila, Internal report, June 2012

Last update: October 26, 2022

2.3. Besides conductivity, what are other important properties of copper?

Copper sets the standard for electrical conductivity but that's not the end of the story. Cf the attached data-sheet, copper has also desirable thermal, mechanical, electrochemical and alloying properties which explain its more than a hundred application areas as a base metal.

Metals that have good electrical conductivity also have high thermal conductivity. So copper is also a material of choice for highly efficient, compact heat exchangers for use in refrigerators, heat pumps, air conditioning equipment, solar thermal panels, district heating systems or industrial applications.

Good mechanical properties such as creep and fatigue resistance make copper perform in electrical contacts. These properties ensure the ability to make reliable and safe fixed contacts in electrical systems that last for decades. For non-fixed contacts, copper is often alloyed to improve strength.

Mechanical properties also influence copper's malleability. Copper can be drawn into wires as tiny as 50 microns (half the diameter of a human hair). Thin copper wires can be stranded into flexible cables which are easily installed with a low bending radius. Malleable copper also enables the production of musical instruments, works of art, furniture frames and a huge number of other products.

Copper has electrochemical properties that yield a further set of advantages. Copper is corrosion-resistant and can therefore be used for several hundred years in outdoor applications without corroding. It is also used for this property in marine applications, in demanding chemical environments, for high integrity earthing systems or for bare overhead conductors in coastal regions. In the future, these properties may be further exploited in energy storage applications, advanced metallurgical processing or catalytic applications.

Finally, copper can be easily alloyed. About 20% of copper is used in its alloyed form through over 400 alloys to improve strength, corrosion resistance, micro-alloys for high strength and conductivity, wear resistance, machinability or heat resistance.

References

[1] Data-sheet - copper properties - https://help.copper.fyi/hc/en-us/article_attachments/5928673006994/Data_sheet_-_copper_properties.docx

[2] Copper is ... - https://help.leonardo-energy.org/hc/en-us/articles/4801948918034

Last update: June 6, 2022

2.4. What is the color of copper?

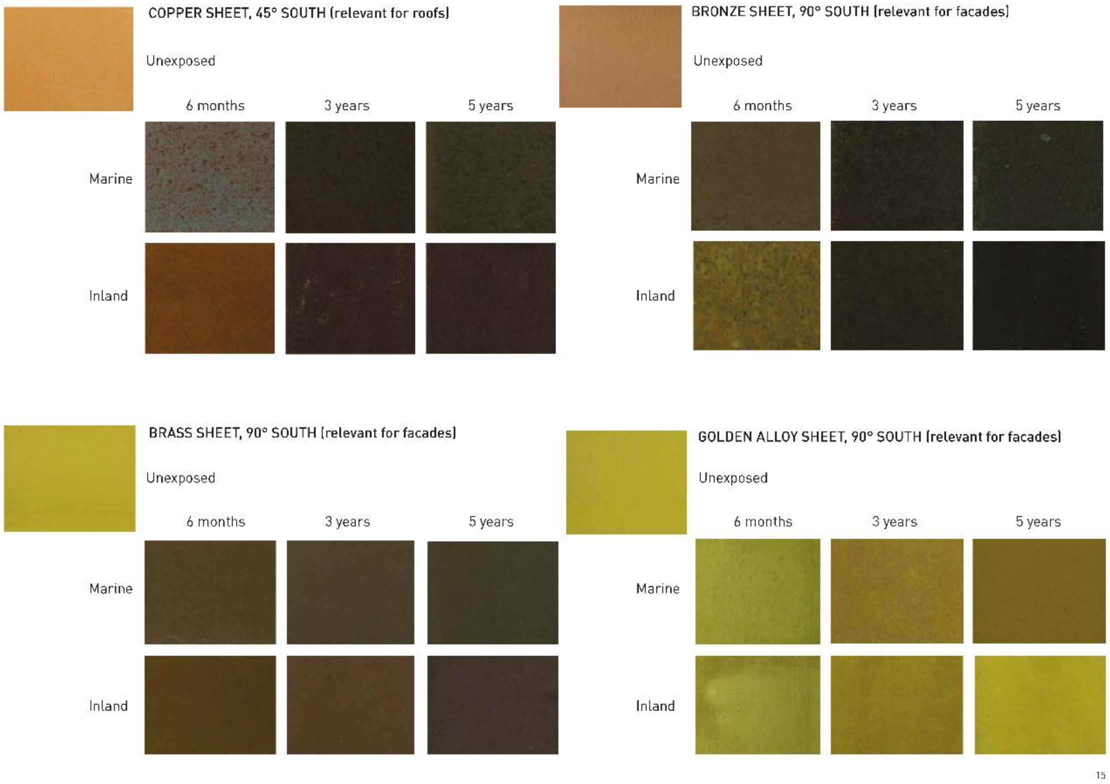
Besides gold, copper is the only metal that is colored. Since it also occurs in nature in its native form, and is more abundant than gold, we can speculate that copper was the first metal ever recognized by humankind though gold is the first metal ever used for ornaments. Our ancestors must have been intrigued by those brownish/reddish stones.

Copper is often called "the red metal", probably for the reddish appearance of newly produced wire rod for wire & cable, which represents about 60% of copper use. It is however not a pure red. A discussion with a colleague from France reveals that they concluded on defining the color as 'salmon pink', which makes sense upon a closer look.

When insulated or coated, copper's color will not change, but when exposed to air, oxidation will gradually change the color to brown. Sometimes, heat accelerates this process. E.g. new copper tube will look reddish just like wire rod, but with time, it becomes brown. End-of-life copper scrap shows a similar color.

Alloying in combination with surface treatment can provide a spectrum of colors as shown below:

Further diversity comes when copper is used in outdoor applications and exposed to a combination of water, atmospheric conditions (e.g. salinity) and solar radiation.



Copper's colors, in combination with its malleability and durability make it also a popular and versatile material in the arts.

References

Copper is ... - https://help.leonardo-energy.org/hc/en-us/articles/4801948918034

How Copper and Copper Alloy Surfaces Evolve - https://issuu.com/copperinarchitecture/docs/surfaceevolutioneng_6742e3ff45d3d9 (accessed November 9, 2022)

Surface appearance of copper-based materials at unsheltered marine conditions - https://issuu.com/copperinarchitecture/docs/151110cubrochurekth (accessed November 9, 2022)

Copper in the arts (2007 - 2022) by CDA Inc - https://copper.org/consumers/arts/ (accessed November 9, 2022)

Last update: November 23, 2022

3. Copper resources

3.1. How much copper has been mined since the dawn of mankind?

Thanks to ICSG, we have good copper production statistics since 1900. But copper metallurgy has supported human development over sixty centuries. How about the other 59 centuries?

Using the references below, we can estimate some datapoints to derive copper production from the Bronze age.

Era	Copper production over the era	Cumulative production
Bronze age (-2000 to -700)	1 million tonnes	1 million tonnes
Roman era (-250 to +350)	5 million tonnes	6 million tonnes
From the fall of the Roman era to 1800	8 million tonnes	14 million tonnes
Industrial revolution (19th century)	36 million tonnes	50 million tonnes
20th century	412 million tonnes	462 million tonnes
21st century (2001 to 2021)	360 million tonnes	822 million tonnes

Compared to the 452 million tonnes of copper in use in 2018, 759 million tonnes had ever been mined in 2018, i.e. 60% of copper that had then been mined was still in productive use.

However, one could note a strong acceleration of copper use: 60% of 452 million tonnes is also the amount of copper that has been mined over the period 1986-2018. Pretty soon, we'll have mined as much copper in the 21st century as in the previous six millennia.

This leads to important questions such as whether the copper sector is ready to support 21st century copper demand and how this can be done in an environmentally and socially responsible manner. These are questions that we'll address elsewhere in this tutorial, and which can only be answered in dialogue with local, regional and global stakeholders.

References

- Hong, S., J. P. Candelone, and C. C. Patterson. 1996. “History of Ancient Copper Smelting Pollution during Roman and Medieval Times Recorded in Greenland Ice.” Science. https://science.sciencemag.org/content/272/5259/246.abstract.
- Fizaine, Floriant, and Xavier Galiegue. 2021. L’économie des ressources minérales et le défi de la soutenabilité 1 - Contexte et enjeux. https://www.istegroup.com/en/produit/leconomie-des-ressources-minerales-et-le-defi-de-la-soutenabilite-1/ (checked October 21, 2021)
- Fizaine, Floriant, and Xavier Galiegue. 2021. L’économie des ressources minérales et le défi de la soutenabilité 2 - Enjeux et leviers d'action. https://www.istegroup.com/en/produit/leconomie-des-ressources-minerales-et-le-defi-de-la-soutenabilite-2/ (checked October 21, 2021)

Last update: June 17, 2022

3.2. How is copper found (about copper exploration)?

Prospection and exploration are the first steps in the life cycle of a greenfield mine. These are overlapping stages which take years, and if successful, gradually evolve into development. A typical process takes 2 to 8 years, but sometimes, the process is halted, e.g. for lack of finance, a change in political climate or a market cycle, to be resumed later.

For greenfield exploration, one seldom sets out to discover copper specifically. Prospectors search for valuable minerals. However, striking copper is never bad news, especially if it comes with some of copper's typical byproducts such as Ag, Au or Mo.

Exploration takes place in both existing and new locations. For new locations, particularly in remote areas, the licencing process is somewhat easier, but exploration and development are more expensive. Once an asset moves from development into production, (brownfield) exploration remains a continual process to find new areas to extract within a deposit.

Prospection starts with an idea, a theory, followed up by satellite imaging, drone photography or Landrover exploration. It may be followed by geophysical and geochemical analysis, then by a drilling programme. Exploration creates vast amounts of data put in 3D maps to identify areas of interest.

Prospection is highly risky business. Less than one in a hundred geochemical explorations eventually develops into a mine. When starting from Landrover exploration, the ratio is probably closer to 1/1000. Throughout the process, investment decisions are made to proceed or not.

ICA members have their own prospection/exploration departments, but they also partner with junior miners who develop prospection portfolios. In many cases, a junior miner will sell its project to a mining company for development. Sometimes junior miners further develop the project themselves, sometimes, they enter into joint-ventures with partners to cover capital and expertise needs.

The goal of exploration is to determine the size and value of a deposit, and what it will cost to mine it. Exploration requires a licence which is time-limited ("use it or loose it"). Exploration involves a drilling programme to take multiple samples in different places at different depths to classify the mineral resource from inferred to indicated and measured. The part of the resource that can be mined economically is the ore reserve.

Investment levels increase significantly as exploration proceeds. The whole exploration cycle can cost 0.5 ... 15 M$. The economics are 0.5 … 2 $ return to the dollar invested. Drilling a borehole in the Arctic or the Atacama desert costs around 100,000 $. Drilling programmes in sedimentary rock (e.g. Lubin) are substantially more expensive (up to 1 M$/hole). The number of holes depends on the geometric form, spread and size of a deposit. Soft rock leads to open pit mining, hard rock to underground mining. Depth is another factor - open pit is used for shallower deposits up to a few hundred meters. Below one km depth, mining will be underground. Demand for a mineral in 2, 5 and 10 years is a key factor for the investment decision. Considering the risk, junior explorers pursue a portfolio approach.

There are daily online reports on exploration results which vary from a general idea to an investment-grade report on the results of a drilling programme. Considering the high risks and the amounts of capital involved, the reporting of exploration results is highly regulated through standards or codes of conduct. The JORC code is used in the Eastern hemisphere (Australia, Asia), whereas the Canadian Institute of Mining publishes National Instrument 43-101. Additional codes are available in mining countries such as South Africa, Russia and Poland.

The final outcome of exploration is a feasibility report. Development of a project typically requires 10 to 20 k$ investment per tonne of annual copper production leading quickly to multi-billion $ investments. The feasibility report includes an environmental and community impact assessment.

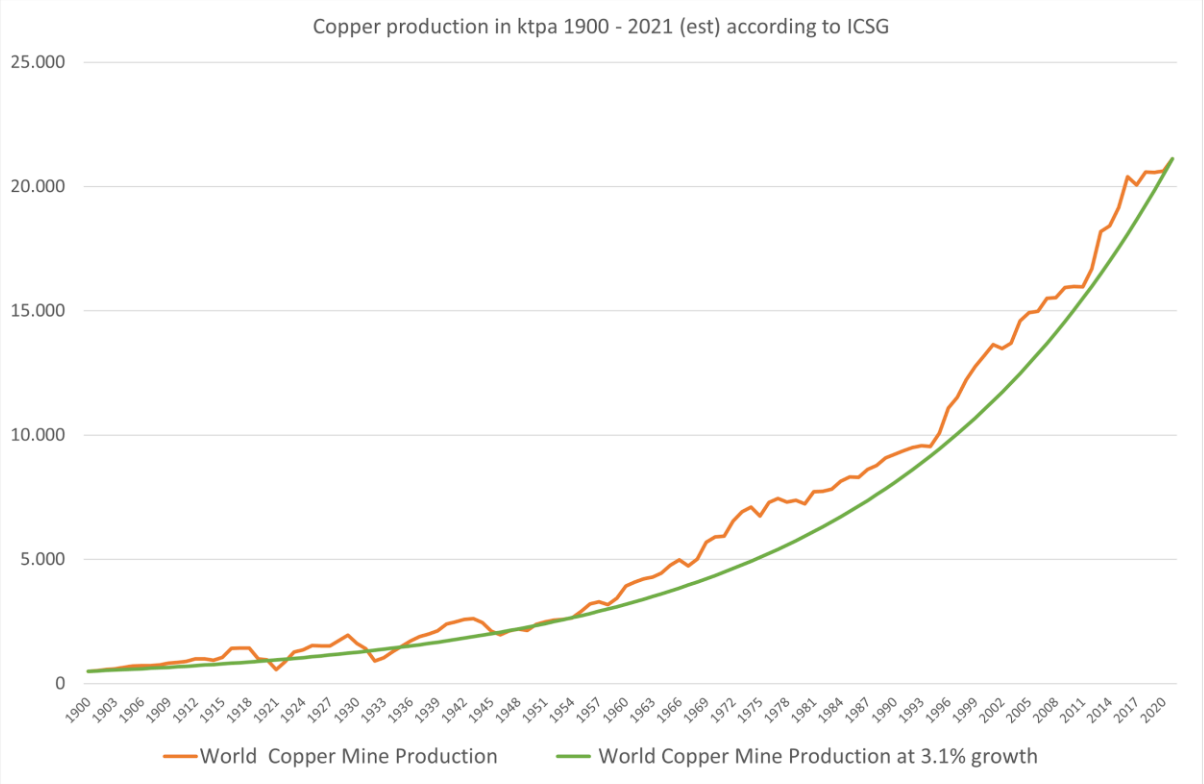
References

- Superfund Research Center: Copper Mining and Processing (checked January 21, 2022)
- E-learning course: the business of mining (checked November 24, 2021)
- Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves, 2012 edition (checked December 22, 2021)
- National Instrument 43-101 Standards of Disclosure for Mineral Projects, 2016 edition (checked December 22, 2021)

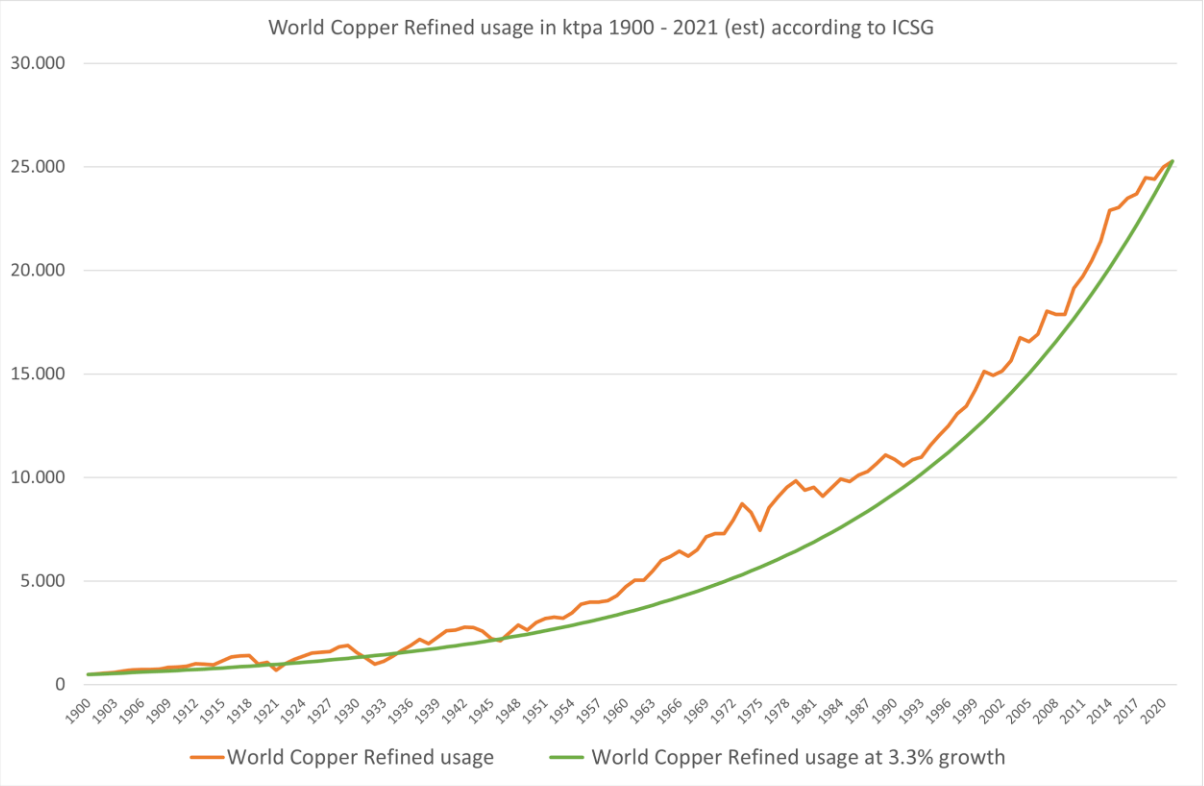
Last update: January 21, 2022

3.3. How has copper production evolved since 1900?

Referring to cumulative copper production since the dawn of humankind, 94% of the world's copper production has been extracted since 1900. The data fits reasonably well an exponential growth curve with a compound annual growth rate (CAGR) of 3.1 percent.



From ICSG, we also have a long time series on refined copper usage which is initially identical to mining production, but as the stock builds up and copper applications reach the end of their useful life, secondary copper resources begin to add to primary copper production. Hence the CAGR for refined copper production is slightly higher: 3.3%.



Sometimes, the comment is made that "we'll mine as much copper in the coming 25 years as since the past 4000 years". While this comparison is about right and sounds impressive, it is what the copper industry has been delivering since the 40s:

Year	Annual mining production (ktpa)	Cumulative production since the dawn of humankind (Mt)	Growth of cumulative production over a 25-year period
1921	558	68	-
1946	1 959	112	1.64
1971	5 941	205	1.83
1996	11 084	412	2.01
2021	21 124 (est)	822	2.00

Reference

Data for World Copper Mine Production and World Copper Refined Usage for 1900 - 2021 (est) provided by ICSG.

Last update: February 28, 2022

3.4. What are by-products of copper production?

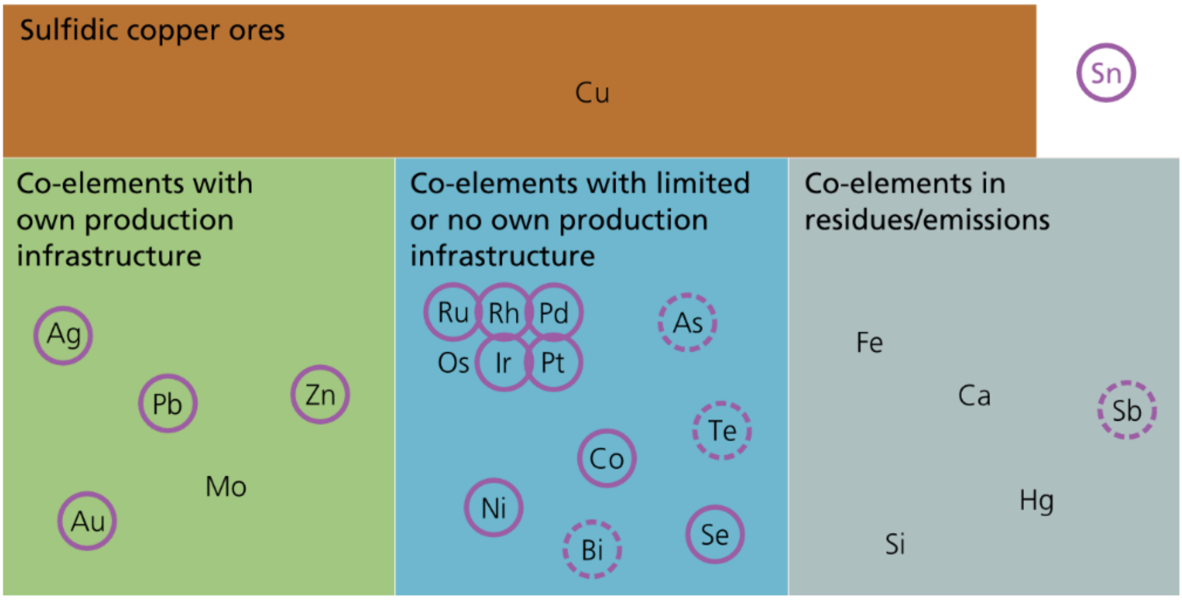
Copper is seldom mined alone and comes with a range of by-products. Some of these metals are economically very important (e.g. gold and silver). They contribute to the profitability of a mining operation and are usually accounted for as negative costs. Others are important because of their toxicity which needs to be adequately managed while these metals might find limited uses in specialised applications (e.g. arsenic, cadmium or thallium). A third group of elements serves significant and often growing market niches.

For some of these elements, copper mining complements the production infrastructure of the by-product (e.g. gold, silver, lead, zinc or molybdenum). Other minor metals have limited or no own production infrastructure (e.g. selenium or tellurium).

Hereby a list of commonly found by-metals in copper mining with a few of their applications:

- **Bismuth**: low melting alloys for soldering or as an additive to improve machinability
- **Cobalt**: superalloys, batteries
- **Gold**: jewelry, electronics, monetary uses. Freeport's Grasberg mine is one of the world's largest deposits for both copper and gold.
- **Molybdenum**: alloying element, catalyst, wires for high-temperature heating. Codelco is one of the world's largest molybdenum producers.
- **Nickel**: stainless steel, superalloys, batteries.
- **Rare Earth Elements**, e.g. cerium, dysprosium, lanthanum, neodynium, praseodynium: alloys, magnets
- **Rhenium**: superalloys, catalyst.
- **Selenium**: glass industry, silicon cells, food additive. The world's largest producer is RETORTE, a subsidiary of Aurubis.
- **Tellurium**: steel or copper additive to improve machinability, element for thin-film photovoltaics. Rio Tinto will build a plant to recover tellurium at its Kennecott mine.
- **Silver**: reflective coatings, jewelry, imaging, medical devices, high performance batteries, catalyst. KGHM is one of the world's largest silver producer.

The figure below provides a graphical overview of the many by-products of copper smelting and refining that can be obtained both from primary and secondary sources (enclosed by solid circles: cobalt, gold, lead, nickel, most platinum group metals, selenium, silver, zinc) while for some, the origin—primary or secondary source - is not quite clear from published documents (enclosed by dashed circles: antimony, arsenic, bismuth, tellurium). Finally, tin is recovered exclusively from secondary sources.



Based on Reuter (2005), Umicore (2010), www.aurubis.com, Sundqvist (2013), Isaksson & Lehner (2000)

References

- Aurubis, Metals Lexicon. August 2012.
- Study of By-Products of Copper, Lead, Zinc and Nickel, https://www.oakdenehollins.com/reports/2014/1/15/study-of-by-products-of-copper-lead-zinc-nickel-executive-summary (accessed August 2012, 2021)
- USGS Critical Minerals List. https://www.usgs.gov/centers/nmic (accessed August 2021)
- Brief overview of by-products in secondary copper production, internal report by Fraunhofer for International Copper Association, November 2015

Last update: October 19, 2021

3.5. How are exploration results reported?

Exploration is an expensive and high-risk process, yet it can be highly profitable. Less than one in a hundred projects results in a mine. Check an exploration report for details and whether the report follows an established code. Examples of codes can be found in the following list:

- Australia's Joint Ore Reserves Committee (JORC) code (AusIMM et al., 2012);
- Canada's National Instrument 43-101 (NI43-101; OSC, 2011) and associated CIM code (CIM, 2014);
- South Africa's Mineral Resource Code (SAMREC) code (SAMRCWG, 2009);
- U.S. SEC's Industry Guide 7 (SEC, 2007);
- Europe's Pan-European Resource Reporting Code (PERC) (PERC, 2013);
- Peru's Code (JCVCS-LSE, 2003);
- The Philippines' Mineral Reporting Code (PMRC) (PMRCC, 2007);
- as well as similar codes in many other countries (e.g. China, Russia);
- and technical or academic guidance from professional societies (e.g. AusIMM, 2014; Noble, 2011; Rossi and Deutsch, 2014).

The CRIRSCO defines a reporting template for exploration results, mineral resources and mineral reserves. A clear distinction between various types of resources and reserves is essential, though stakeholders inside and outside the mining sector, intentionally or unwittingly, often confuse these classifications.

Reference

Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply

CRIRSCO International Reporting Template

How is copper found?

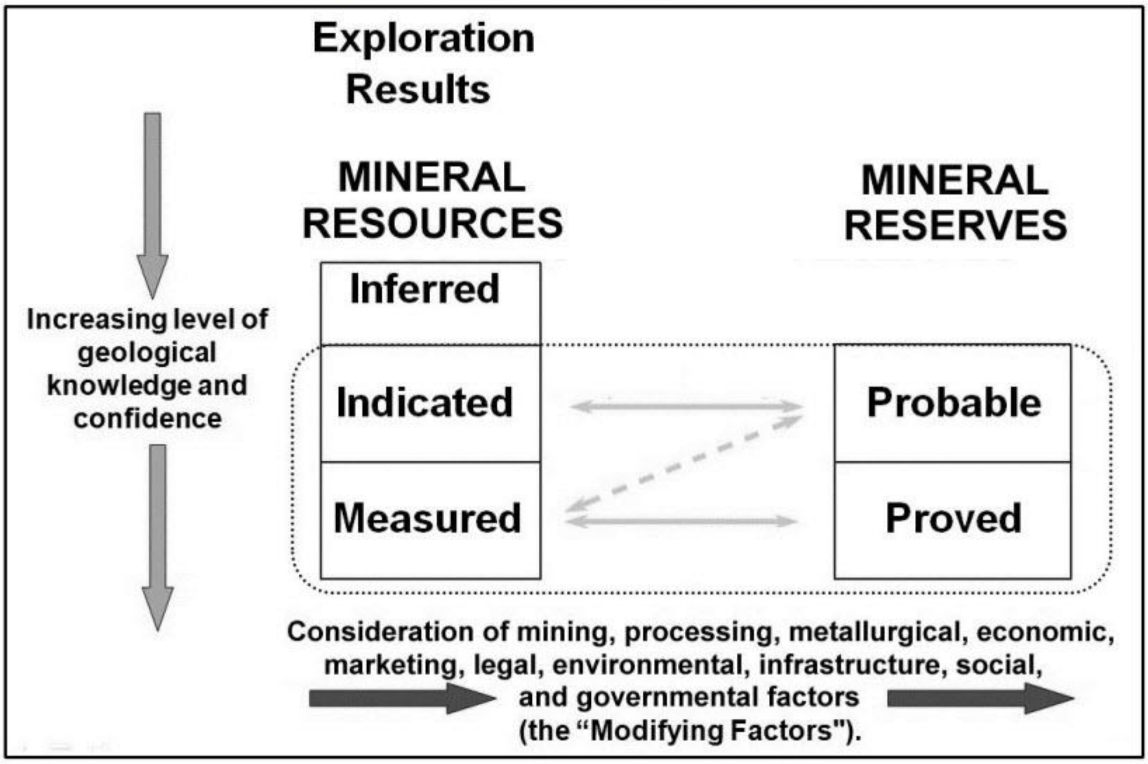
Last update: July 7, 2023

3.6. What's the difference between exploration results, resources and reserves?

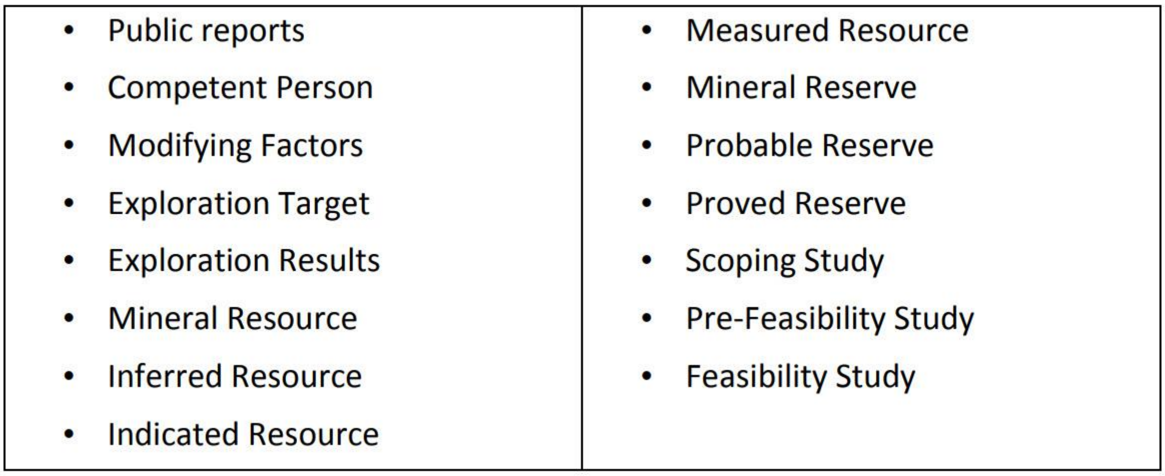
Exploration is a process of gradual discovery. It's essential to distinguish between the exploration results for resources and the conversion of these resources into mineable reserves.

CRIRSCO defines a framework for how exploration results evolve to various types of resources and reserves.

General relationship between Exploration Results, Mineral Resources and Mineral Reserves



It also provides a clear definition of terms (for use in its reporting template).

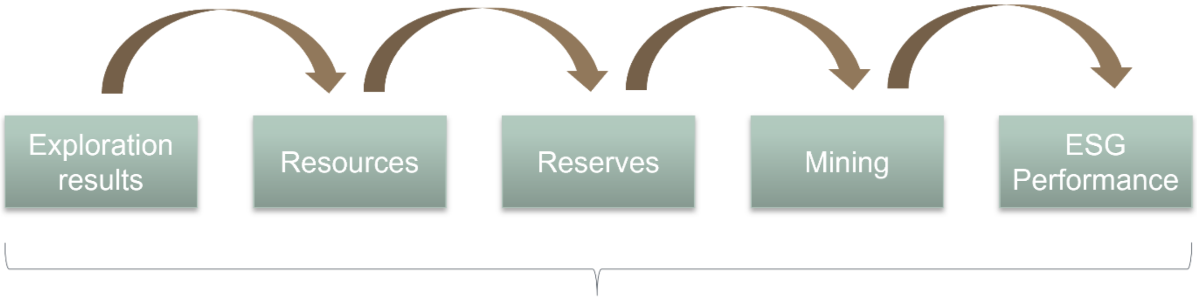


- Public reports
- Competent Person
- Modifying Factors
- Exploration Target
- Exploration Results
- Mineral Resource
- Inferred Resource
- Indicated Resource
- Measured Resource
- Mineral Reserve
- Probable Reserve
- Proved Reserve
- Scoping Study
- Pre-Feasibility Study
- Feasibility Study

A review paper by G Mudd et al provides a comprehensive overview of known resources. It compares resource assessments between 2010 and 2015, concluding that resources have increased 13% per annum in this period, from 1.8 to 3.1 Gtons. There are three drivers for this increase:

> "First, this study is more comprehensive, with an increase in deposit numbers (730 vs. 2,301). Second, there have been new discoveries made (or rather resources outlined) between 2010 and 2015. Third, a significant proportion of resources within the 2010 study have grown in size (by a mean value of 13%), often coincident with significant amounts of production."

A key message from the paper is that while copper resources continue to grow with production, it's the modifying factors to convert resources to reserves and eventually into production that are currently the major bottleneck.



Modifying factors: mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors.

During the lifetime of a mining project, reserves may well increase as new brownfield exploration results or technological innovation reveal new possibilities. The opposite can happen as well - an incident in a mine could degrade a reserve into a resource.

References

CRIRSCO standard definitions, https://www.crirsco.com/docs/CRIRSCO_standard_definitions_oct2012.pdf, accessed September 16, 2022

Gavin M. Mudd, Simon M. Jowitt; Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. Economic Geology 2018;; 113 (6): 1235–1267. doi: https://doi.org/10.5382/econgeo.2018.4590

Last update: August 21, 2023

4. Mining copper

4.1. How is copper produced?

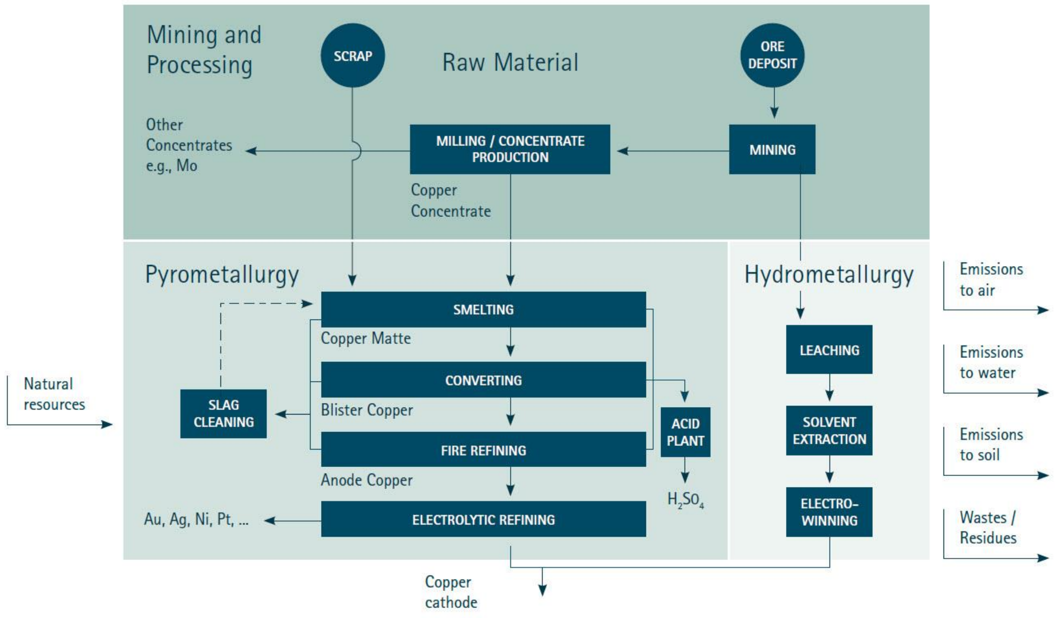
From its original home buried underground in a mine to its use in a finished product such as wire or pipe, copper passes through a long journey.

Primary copper production starts with the extraction of copper-bearing ores. There are two basic ways of copper mining: surface and underground mining. Due to copper being spread in relatively low concentrations over large areas, surface, or open-pit mining, is the predominant mining method for copper in the world.

After mining, copper is produced by one of two process routes: pyrometallurgical or hydrometallurgical. About 80-85% of copper production follows the pyrometallurgical route.

Within the pyrometallurgical route, the mined ore is crushed and milled, followed by a concentration step using flotation. The obtained copper concentrates contain on average 30 percent copper, but grades can range from 20 - 40 percent (ICSG, 2016). In the following smelting process, copper is transformed into a “matte” containing 50 – 70 percent copper. The matte is either flash converted or processed in a converter resulting in blister copper of 98.5 – 99.5 percent copper content. In the next step, the blister copper is fire refined by the traditional process route or re-melted and cast into anodes for electro-refining. The output of electro-refining is refined copper cathode, containing over 99.99 percent copper.

Alternatively, the hydrometallurgical route extracts copper from mainly low grade oxide ores and some sulfide ores through leaching, solvent extraction (also referred to as solution extraction), and electrowinning, often called the SX-EW process. The final product is the same as through the pyrometallurgical route—refined copper cathode containing over 99.99 percent copper. The figure below shows the basic steps in the production of refined copper cathode.



Secondary copper production utilizes a variety of secondary copper containing materials such as copper scrap from metals discarded in either semi-fabrication or finished product manufacturing processes (“scrap from fabrication”) or obsolete end-of-life products (“end-of-life scrap”). These two scrap flows are split into low and high grade scrap (see also the copper flow model). Low grade scrap moves again through a smelter & refining process and produces a secondary copper of identical quality as primary copper. High grade scrap can be directly melted by fabricators to produce copper products that do not need the 99.99% purity required for electrical conductivity applications.

Reference

Copper Environmental Profile, https://copperalliance.org/sustainable-copper/about-copper/copper-environmental-profile/ (checked October 26, 2021)

Last update: November 18, 2021

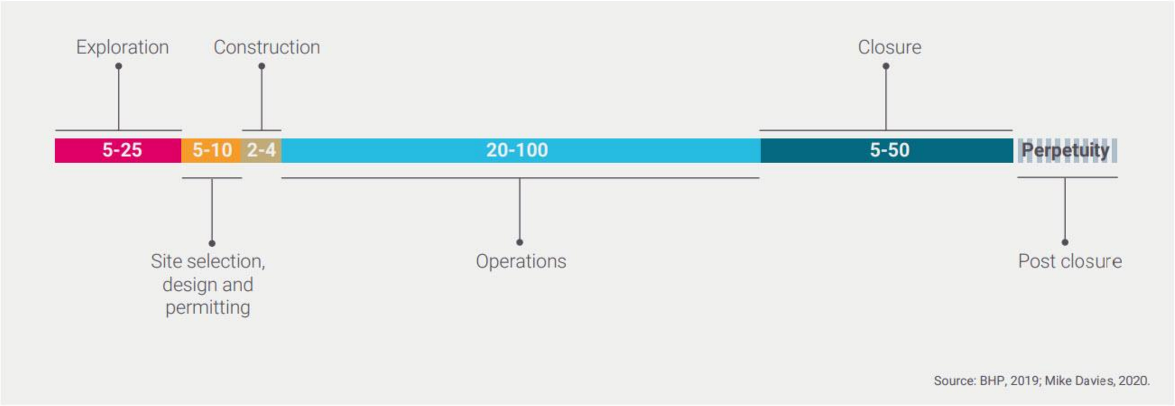
4.2. What's the life of a copper mine project?

Short answer: on average about a hundred years. T

This makes copper a very long-term business as recently mentioned by Freeport's CEO Richard Adkerson in an interview with Bloomberg.

The chart below is an extract from the compendium accompanying the global tailings review - see page 17 of the pdf. A life of over a hundred years is equivalent to ~25 strategic planning cycles or political mandates. It means:

- Considering that growth in copper mining is a relatively recent phenomenon, few mines have gone through their full life-cycle yet. According to ICSG's mining database, there are 488 copper mines in operation, and only 23 mines have been closed. Mining closure is a developing practice with limited experience.
- It is important to have mining companies that are in this business for the long run as is the case for most ICA members. One member's mining history goes even back as far as the 16th century.



Source: BHP, 2019; Mike Davies, 2020.

Figure 2. Life of a mine with a tailings storage facility – in average years

More information about the four stages of a mining project can be found on the page below from the University of Arizona's Superfund Research Center:

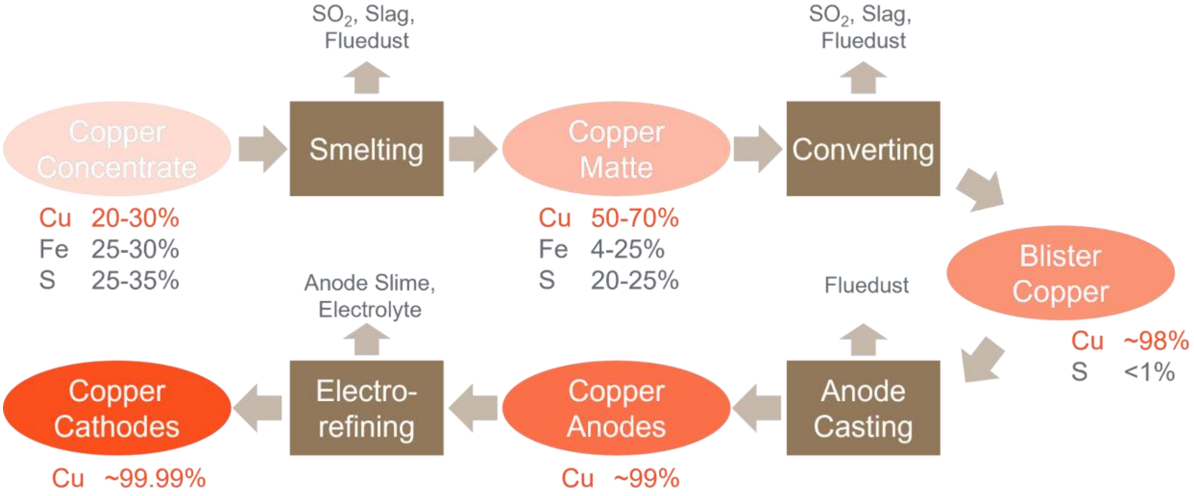
Copper Mining and Processing: Life Cycle of a Mine

Last update: July 27, 2021

5. Smelting and refining

5.1. How a copper smelter works

A basic flowsheet of smelting and refining can be found below:



In a first step, smelting takes place in different types of furnaces depending on the raw materials and the process technology. An upper layer of slag and a lower one of **matte**, which has a copper content of approximately 55% form in the furnace.

The copper matte is tapped into a converter furnace where iron and other impurities, together with sulphur, are separated out. The converter is also charged with scrap metal and, in some cases, black copper – an intermediate product from the recycling of electronics. The result is known as **blister copper**, which has a copper content of 97-98 per cent.

The blister copper is then processed in an anode furnace to reduce its oxygen content. This increases the purity level to 98-99 per cent and the copper is then cast to form **anodes**.

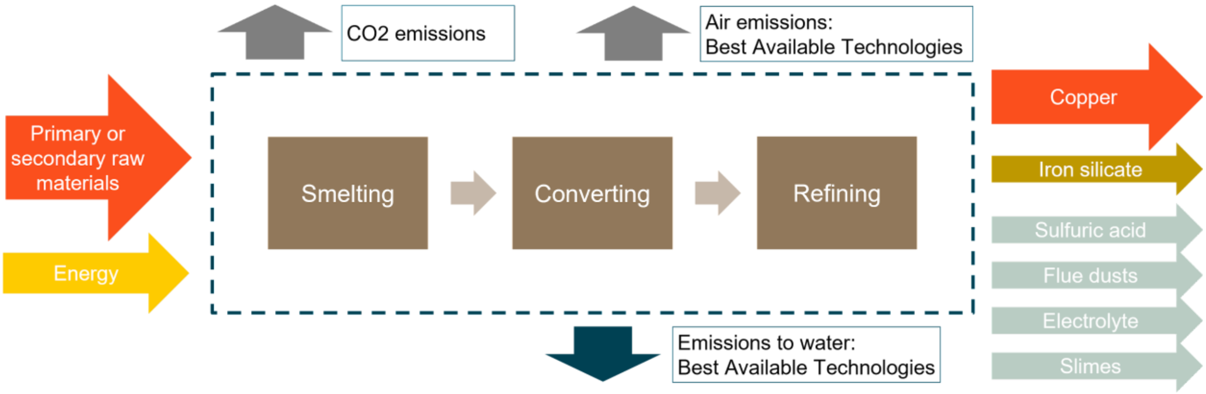
The anodes are placed in tanks with steel cathode plates. In the subsequent electrolytic refining process, copper migrates from anodes to **cathodes**, which ultimately have a copper content of 99.99 per cent or higher.

Cathode cannot be easily processed and will be melted to be cast into wire rod, billets or cakes, the "first uses of cathode":

- **Wire rod** is the term used to describe coils of copper of 6 to 35 mm diameter (typically 8 mm) which provide the starting stock for wiredrawing. This is the most important first use of cathode, representing 60% of all copper used (when including alloys).
- **Cakes** (or slabs) are used when flat plate, sheet, strip and foil are required. They are now mostly cast continuously, which gives an improvement of pieceweight, yield and quality over the earlier static casting methods. Copper is commonly hot rolled from a thickness of 150 mm down to about 9 mm and cold rolled thereafter.

- **Billets**, usually about 250–350 mm diameter, are cast for subsequent extrusion to rod and bar. Normally these are cut to no more than 750 mm in length to fit the extrusion chamber and this controls the maximum pieceweight which may be made. Extrusions are usually subsequently drawn to the required finished sizes by one or more passes through drawblocks.

A smelter that processes secondary raw materials operates in a similar flow. In practice, smelters will often use a mix of primary and secondary materials. The following schematic helps to visualise the main inputs & outputs for the smelting & refining process.



References

[1] Langner, Bernd E. 2011. Understanding Copper: Technologies, Markets, Business. Page 109. Accessed July 27, 2021.

[2] New Boliden. Metals for Modern Life. Pages 16-17. Accessed July 27, 2021.

Last update: August 12, 2021

5.2. What products does a copper smelter produce?

A copper smelter can produce over 20 useful products [1]. The key to running a successful smelter operation is the use of good practices and best-available technologies to minimize waste and maximize product value while carefully managing material streams, energy use and emissions to the environment.

The portfolio of a smelter can consist of:

- Copper cathode, Anodes, Blister copper
- Anode slime: Ag, Au, PGM concentrate
- Iron silicate (final slag)
- Lead, tin, alloys
- NiSO4, CuSO4, other salts
- Selenium, tellurium
- Sulfuric acid
- Zinc oxides
- Other metals such as As, Bi, Ir, Ru, Sb, ...

Not all smelters produce the full range of these products. Smelters specialise in particular material streams (e.g. high purity copper, e-waste, low-grade copper materials, ...) and cooperate to concentrate the processing of specific material streams at a sufficient scale.

Reference

See p27 of Organisation Environmental Footprint Sector Rules – Copper production, February 2020, available from https://ec.europa.eu/environment/eussd/smgp/pdf/OEFSR_Copper_Feb2020.pdf (accessed March 16, 2022)

Last update: March 29, 2022

5.3. What are TC/RCs (Treatment and Refining Charges)?

Custom smelters are offering a service to the mining companies by converting copper concentrates with a copper content of typically 20-25% to copper cathodes.

TCs are charged in US$ per tonne of concentrate smelted. RCs are charged for refining copper anodes to produce copper cathodes by electrolysis. This charge is expressed in ct/lb and refers to the amount of copper in the concentrate.

TCs and RCs are very volatile and can change from year to year as well as within a year. Díaz-Borrego provides a table of historic TC/RCs for the period of 2004 - 2017:

Year	TC (US$/ton)	RC (ct/lb)	Year	TC (US$/ton)	RC (ct/lb)
2004	45	4,5	2011	56	5,6
2005	85	8,5	2012	63,5	6,4
2006	95	9,5	2013	70	7,0
2007	60	6,0	2014	92	9,2
2008	45	4,5	2015	107	10,7
2009	75	7,5	2016	97,35	9,7
2010	46,5	4,7	2017	92,5	9,3

TC/RCs provide part of the revenue of a smelter. E.g. the table below gives an indicative calculation for revenue per tonne of copper for various TC/RC levels and levels of concentration:

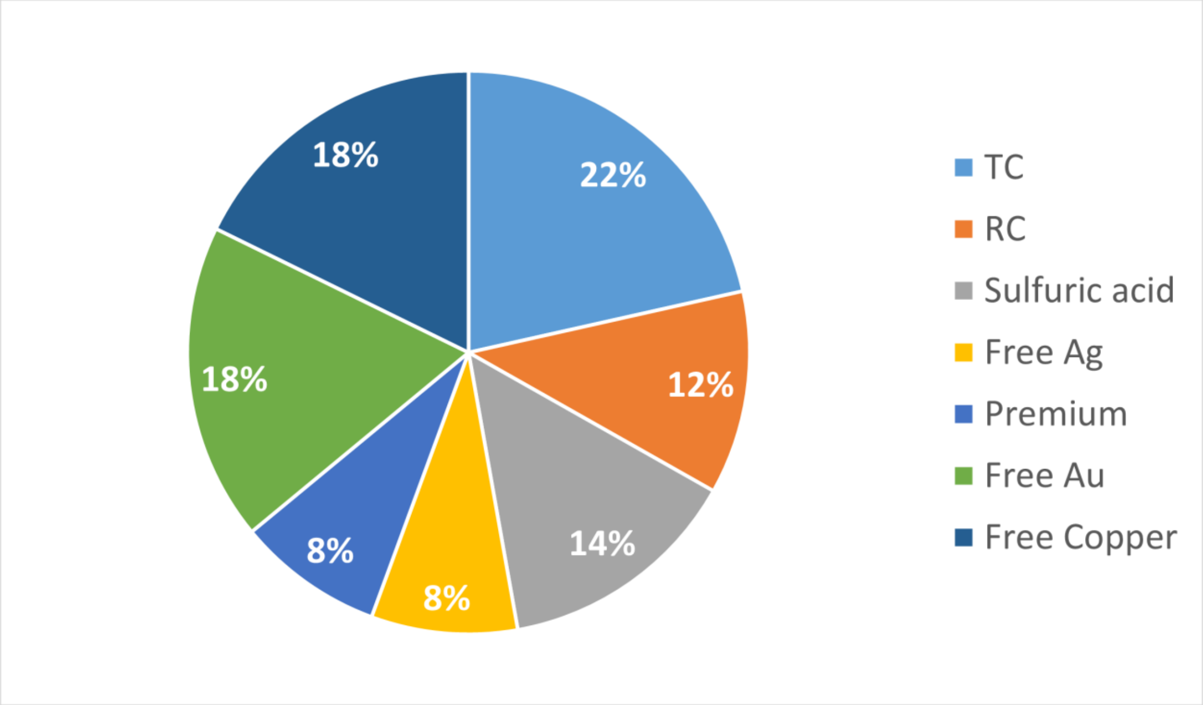
		Level of concentration		
TC ($/tonne)	RC (c$/lb)	20%	25%	30%
45	4,5	324	279	249
55	5,5	396	341	305
65	6,5	468	403	360

75	7,5	540	465	415
85	8,5	612	527	471
95	9,5	684	589	526
105	10,5	756	651	581

Smelters can have other sources of revenue besides TC/RCs:

- Sulfuric acid, although normally, the costs for sulfur fixation in sulfuric acid are higher than the credit for sulfuric acid.
- Free metal, such as additional copper, gold and silver extracted from the concentrate above the amounts estimated.
- Penalties related to the amount of deleterious elements in the concentrate (mercury, arsenic, bismuth, lead tellurium, selenium, antimony, fluoride) above a certain accepted level.
- Innovative revenue streams include the valorisation of residual heat from operations or the use of iron-silicate slags in civil engineering and construction projects.

Langner provides an example of a revenue distribution for a particular smelter. This breakdown is based on assumptions related to concentrate composition, TC/RC, commodity prices and process efficiencies. Such breakdown will vary significantly per smelter as well as with time. In particular, the proportion of TC/RCs in total revenue may be much higher in some cases, as TC/RCs may vary from year to year as well as within a year.



Other breakdowns of smelter revenues are given by Boliden in references, showing TC/RC revenue representing 33 - 54% ot total revenue.

Considering this volatility of revenues and rising energy and climate costs, running a smelter/refiner operation requires skill, prudence and a long-term vision.

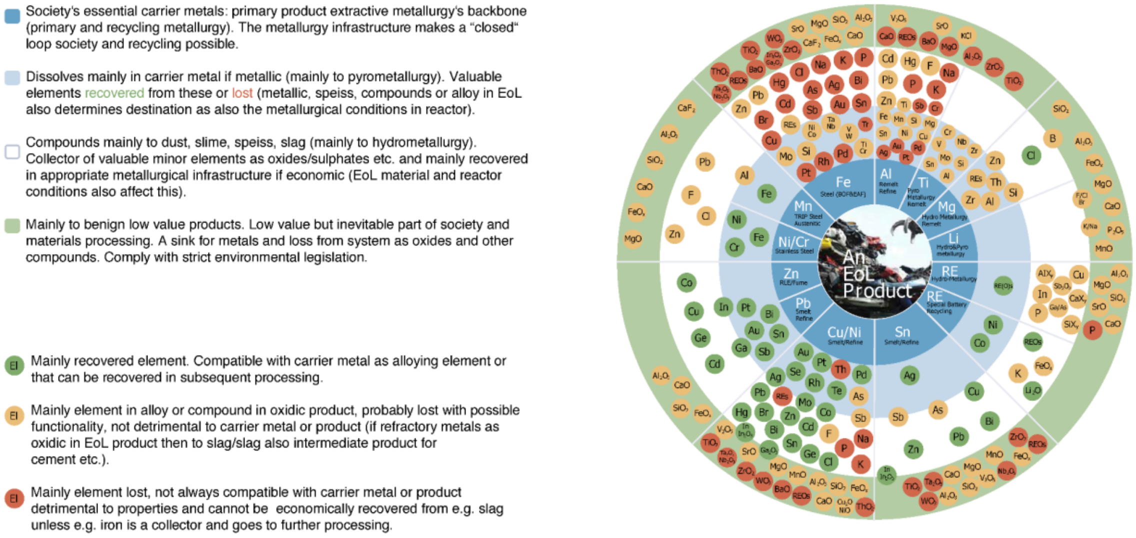
References

- Díaz-Borrego, Francisco J., María del Mar Miras-Rodríguez, and Bernabé Escobar-Pérez. 2019. “Looking for Accurate Forecasting of Copper TC/RC Benchmark Levels.” *Complexity* 2019 (April). https://doi.org/10.1155/2019/8523748. Accessed July 27, 2021
- Langner, Bernd E. 2011. Understanding Copper: Technologies, Markets, Business. Page 168. Accessed July 27, 2021.
- Industrial Heat - A Climate Alliance of Aurubis and enercity. Accessed August 18, 2023.
- See slide 22 of Boliden 2007-2008 or page 46 of Boliden 2021. Accessed March 31, 2022.

Last update: August 18, 2023

5.4. What is the metal wheel?

The metal wheel [UNEP - p 30] reflects the destination of different elements as a function of interlinked metallurgical process technology. Each slice represents the complete infrastructure for carrier metal refining. Consumer electronics contain over 40 different metals. This complexity of consumer products requires an industrial ecological network of interlinked metallurgical production infrastructure to maximize recovery of all elements in end-of-life products.



🟦 Society's essential carrier metals: primary product extractive metallurgy's backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

🟦 Dissolves mainly in carrier metal if metallic (mainly to pyrometallurgy). Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

☐ Compounds mainly to dust, slime, speiss, slag (mainly to hydrometallurgy). Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

🟩 Mainly to benign low value products. Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

● El Mainly recovered element. Compatible with carrier metal as alloying element or that can be recovered in subsequent processing.

● El Mainly element in alloy or compound in oxidic product, probably lost with possible functionality, not detrimental to carrier metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

● El Mainly element lost, not always compatible with carrier metal or product detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

For copper, the metal wheel represents current recycling practice which provides an effective recovery route today for a range of by-products (minor and precious metals). These by-products are generally indistinguishable for metals obtained from primary sources. This positions copper uniquely relative to other carrier metals where alloying elements generally remain with the main metal, as in the case for example for iron or aluminium.

In addition, 80% of copper is used in its unalloyed form and can be fully recycled or even upcycled. The remaining ~ 20% is used in a complex mix of over 400 alloys. Some major alloying elements such as lead, tin or zinc can be removed effectively if required.

Copper's electrochemical properties, the metal wheel, copper's primary use as a conductor and the highly internlinked systems of smelters in place are all factors to position the copper industry well for the upcoming challenges of processing increasingly complex end-of-life waste streams in an increasingly circular economy.

References

- Metals Recycling: Opportunities, Limits, Infrastructure. UNEP & International Resources Panel. 2013. https://wedocs.unep.org/handle/20.500.11822/8423 (accessed August 2021)
- https://www.chemistryworld.com/features/smartphone-recycling/2500497.article (2017 – checked October 2018)
- https://www.youtube.com/watch?v=CWt36I8JgVQ (2011 – checked January 2020)

Last update: December 12, 2021

6. Alloys and foundries

Content in development.

7. From copper to semis

7.1. How much copper is used for conductivity applications?

While copper is used in over 100 applications, electrical conductivity applications represent the major part of global copper use. Cf the attached table highlighting conductivity applications for 2020, these make up 70% of all copper use.

The main use of copper conductors is in wire & cable products, which represented 16.2 million tons in 2020, or 59% of copper use.

Additionally, 11% of copper use flows into conductivity applications for fabricated products used in buildings, infrastructure, industrial equipment, automotive, railways, appliances and industrial electronics. Here are some of the most imported fabricated products for these end-uses:

- Busbars for power distribution, switchgear and breakers.
- Connectors.
- Earthing strip
- Foil for printed circuit boards and batteries.
- Profiles for electrical motors and generators.
- Trolley wire & components for catenary railway systems
- Wide strip and CTC strip for transformers.

Last update: May 3, 2022

8. Products using copper

8.1. Where is copper used in a smartphone?

A smartphone contains between 17 and 26 grams of copper representing 13% of its weight. Besides plastics, iron and aluminium, many of these other elements are often used in small trace amounts for specific applications. Copper is used as a functional material in almost all components of a smartphone:

1. charger
2. headset
3. USB cable
4. antennas
5. battery
6. cameras
7. connectors
8. cover
9. display
10. integrated circuits
11. LEDs
12. microphone
13. Printed Board Area (PBA)
14. Printed Circuit Board (PCB)
15. shields
16. speakers
17. vibrator

In electrical equipment, when a component processes or transfers energy or information, it must rely on copper's conductivity to provide this function using the minimum amount of space with the highest reliability. A single ton of copper provides enough material for at least 50,000 phones and 850,000 components in these phones.

Reference

See p 72 - 74 of Investigating the potential circularity of a phone using Life Cycle Assessment (accessed May 15, 2023)

Last update: May 15, 2023

9. Systems using copper

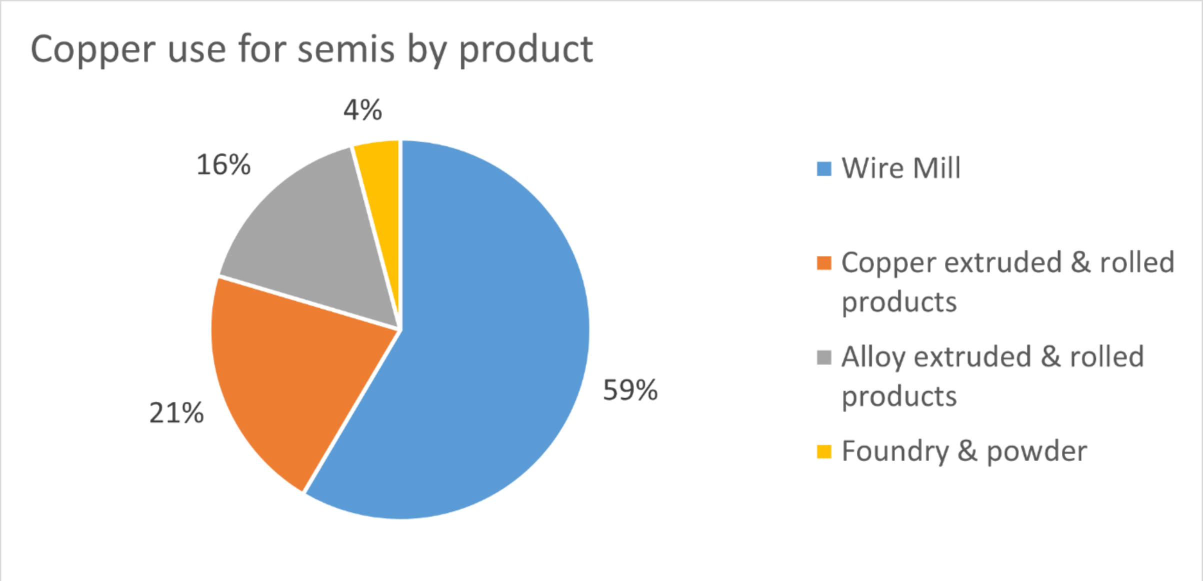
9.1. Where is copper used?

Copper is a material that flows into products (e.g. wires, busbars, tubes, ...) that are used in components (e.g. motors, transformers, cables, ...) to build systems that produce benefits for end-users. When copper leaves the copper industry, it starts a long and complex journey.

The end-use dataset provides good indications where and how copper is used.

By product

Overall, 60% of copper use in in wire & cable products. Roughly a quarter of extruded and rolled products are for electrical conductivity applications, bringing the total for conductivity to 70%. Non-alloyed copper products represent 80% of use with the remaining 20% is spread over 400+ alloys.



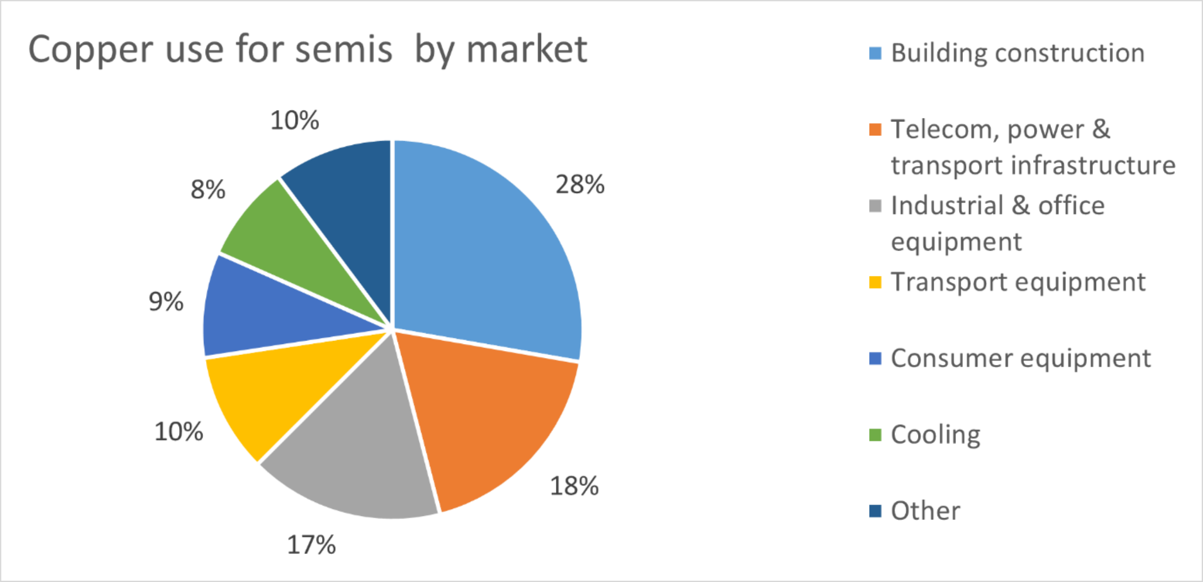
By market

The building construction market represents almost 30% of end-use. This segment covers fixed technical installations in buildings (data, electrical, heating, water). Among these, electrical installations are the most important application.

Power, telecom and transport networks represent close to 20%. Power infrastructure dominates.

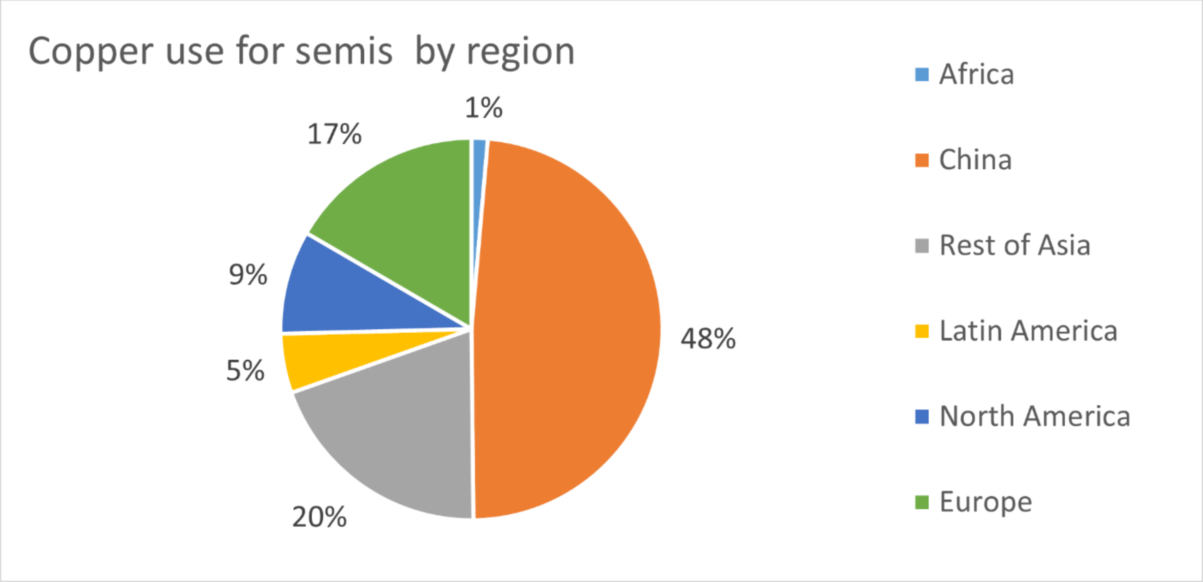
Around 45% of copper is used in manufactured goods - consumer, HVAC, industrial, office and transport equipment.

Finally, 10% covers 'the batallion of everything else', copper in coins, ammunition, clothing, toys, etc.



By region

China represents close to half of refined copper usage and total Asia even 70%. Looking at trade figures, millions of tonnes of copper use in China are embedded in exports for appliances, cars, machinery etc.



Reference

These graphs are based on row and column totals of the 2021 copper semis end-use dataset (data for the year 2020) available at https://help.copper.fyi/hc/en-us/articles/4408226152082

Last update: November 22, 2022

9.2. What are the benefits of copper in use?

Copper is a base metal that is used in thousands of copper products to build components such as motors, transformers or cables that are used in systems such as technical installations in buildings, electricity grids or renewable power plants. In these systems, copper provides significant benefits in use:

> **Energy efficiency**: copper sets the standard for electrical conductivity. Copper's conductivity is only surpassed by silver (at much higher cost). Copper performs 50% better than gold, and 66% better than the next practical alternative - aluminium. And considering that thermal conductivity in metals correlates well with electrical conductivity, copper is also a good conductor of heat.
>
> **Circularity**: since 80% of copper is used in its unalloyed form, it is relatively easy to recycle. As for more complex waste streams, copper's electrochemical properties allow it to reduce most unwanted impurities to the ppm level.
>
> **Compactness**: copper's compactness saves 8 - 25% on other materials in machine design, compared to aluminium designs with the same efficiency.
>
> **Safety**: copper is present in nearly all contact applications. Copper's mechanical properties ensure durable contacts and avoid safety hazards in electrical installations.
>
> **Longevity & reliability**: copper conductors and connectors seldom fail. When performance matters, copper is used, extending the lifetime of equipment and systems.

Copper's sustainability needs to be considered over its full life cycle, considering its potential impacts in production, its benefits in use and its contribution to circularity at the end of its first life in components and systems.

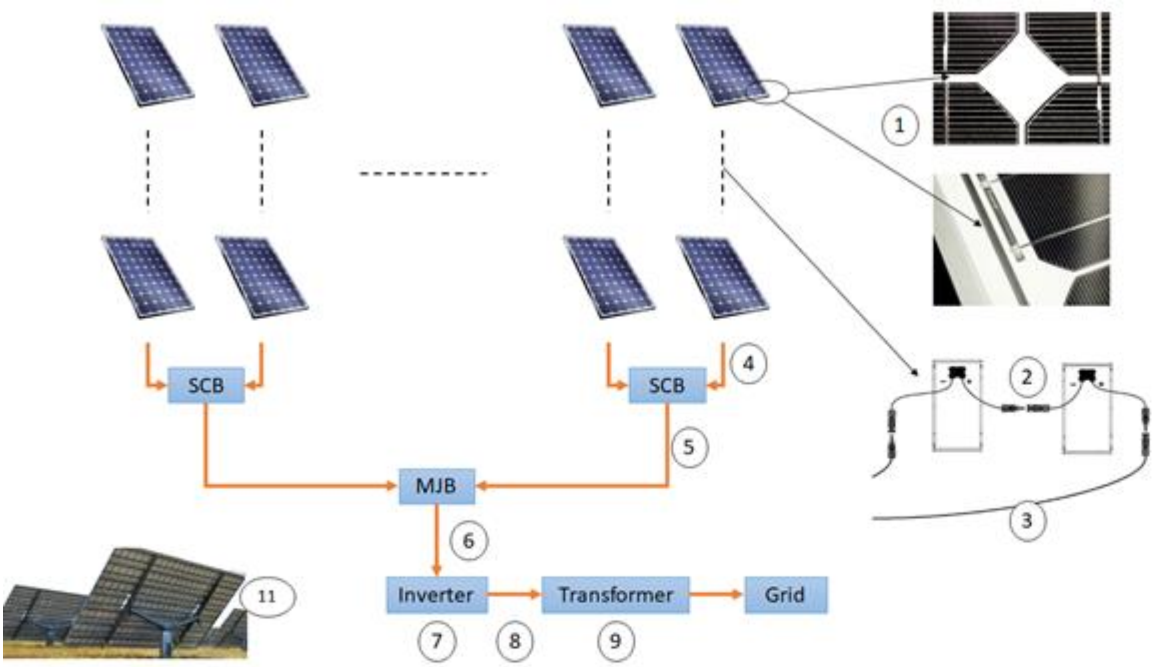
Last update: June 30, 2023

9.3. Copper in photovoltaic power systems

The copper intensity of use (tCu/MWp) in photovoltaic power systems depends on several factors. Copper use can vary from around 2 tCu/MWp to more than 5 tCu/MWp. Some of the major factors determining this use are:

- The size of a plant - as with most energy systems, smaller plants have to a higher copper intensity of use.
- The types of panels used.
- The scope of reporting - about a quarter of copper is used on the panels, and three quarters in the balance of plant.
- The choice of the conductor material, particularly for the cabling and transformer in the balance of plant.

Referring to the picture below, copper can be used in 11 parts of a photovoltaic power system:



1. PV cells (ribbons, busbars)
2. Module cables
3. Panel interconnection cables
4. String controller box, feeding cables
5. Main junction box, feeding cables
6. Inverter feeding cables
7. Inverter
8. Transformer feeding cables
9. Transformer
10. Earthing
11. Tracker feeding (not applicable for fixed tilt installations)

References

- Navigant, 2018, North American Solar PV Copper Content Analysis, report for Copper Development Association
- IEA-PVPS, 2020, Trends in Photovoltaic Applications 2020
- IEA-PVPS, 2020, Life Cycle Inventories and Life Cycle Assessments of Photovoltaics Systems

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Last update: April 6, 2022

9.4. Copper in wind power plants

The copper intensity of use (tCu/MW) in wind power systems depends on several factors. Copper use can vary from around 2.5 tCu/MW to more than 8 tCu/MWp. Some of the major factors determining this use are:

- The size of a plant - as with most energy systems, smaller plants have to a higher copper intensity of use.
- The wind generator technology used.
- The connection to the electricity grid.
- The choice of the conductor material, particularly for the cabling and transformers.

Copper can be used in the following components of a wind power system:

1. Generator
2. Turbine power converter
3. LV cable
4. Turbine transformer
5. Turbine switchgear and busbar
6. Turbine earthing
7. Substation transformer
8. Substation switchgear and busbar
9. Substation earthing
10. Lightning protection
11. MV array cable (offshore only)
12. Export cable (offshore only)

Last update: April 6, 2022

10. End-of-life and recycling

10.1. What is the average lifetime of copper in use?

The Copper Tutorial received the following question:

> *"What is the average lifetime of copper in major/known applications like power cable for transmission, power cable in cars/electrical installations, wire in motors and transformers, copper tube, copper roof?"*

In the Copper Flow model, we find the table below about copper's expected lifetime in 16 end-use applications. These lifetimes have been estimated as follows: first, a starting value was extracted or derived from the existing literature; then, these values were cross-checked in a global survey of experts from the copper industry as well as from related organizations.

While there remains some uncertainty on these numbers, especially for applications with very long lifetimes such as architecture or power cables, they represent a best possible estimate to a complex question.

Taking a weighted average over these 16 applications (using the end-use dataset), **copper's lifetime in use can be estimated to be around 25 years**.

End-use application	Expected lifetime (years)	End-use application	Expected lifetime (years)
Plumbing	40	Non electrical industrial	20
Building plant	40	Electrical automotive	13
Architecture	50	Non electrical automotive	15
Communications	30	Other Transportation	25
Electrical power	40	Consumer and general products	13
Power utility	35	Cooling	12
Telecommunications	30	Electronic	8
Electrical industrial	15	Diverse	15

References

- See table S4, page S14 in Supporting Information - A dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators & uncertainty evaluation (checked June 2021)
- You can verify the calculation in this article using the attached spreadsheet.

Last update: August 18, 2023

10.2. How much copper is used in its unalloyed form?

A major portion of copper end-use is ‘pure’ copper. In comparison, iron and aluminium are predominantly used in their alloyed forms.

So, what is the percentage of pure copper in final use? The end-use dataset provides us a basis for an estimate. Out of the total 27.6 million tonnes of copper input into semis production, all lines represent pure copper with the exception of:

- Alloy tube - 0.3 million tonnes
- Alloy rods, bars and sections - 2.1 million tonnes
- Alloy plates, sheets and strips - 1.7 million tonnes
- Mechanical wire - 0.4 million tonnes
- Castings - 1.1 million tonnes

This yields 22.0 million tonnes of copper in its unalloyed form and 5.6 million tonnes of copper alloy products, representing respectively 80% and 20% of the copper market. In comparison, 90% of all metals are used in the form of alloys - largely alloys of iron, aluminium, nickel or titanium.

In addition to the metal wheel and copper's by-products, copper's predominant use in its unalloyed form help to define its contribution to circularity.

Like other metals, copper recycling also has some key challenges that we'll develop elsewhere in this section.

References

W. H. Dresher and D. R. Poirier, Metal Alloys and Mixtures: Definitions, Behaviour and Characteristics, ICME, 1997, page 1.

Last update: March 3, 2022

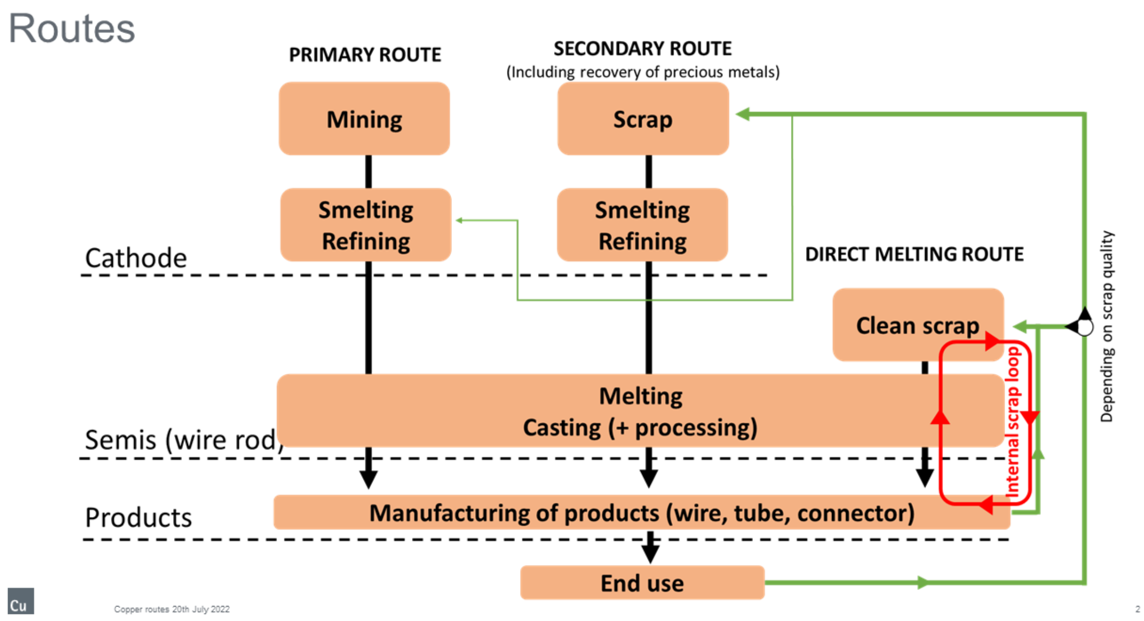
10.3. How much energy and greenhouse gas emissions are saved when recycling copper?

Cf the copper flow model, copper is recycled as "scrap from fabrication" or "as collected & separated into various end-of-life scrap streams". On an annual basis, these two flows combined produce about 8 - 9 million tonnes of secondary raw copper materials to complement the 20 million tonnes of copper being mined. Schematically, these secondary streams split into "low grade copper scrap for smelting & refining" (the "secondary route") and "directly melted high grade copper scrap" (the "scrap route").

Typical values for energy and greenhouse gas savings for these routes, compared to primary production, can only be given as a range. It depends on the product, composition and recycling route. The following table gives some indicative numbers:

(compared to primary production)	Secondary route	Scrap route
Energy saving	-50% ... -65%	-80% ... -90%
Greenhouse gas savings	-60% ... -70%	-85% ... -95%

In practice, the flow of secondary resources in the copper value chain is more complex, cf the diagram below. For example, cf the lower right corner, there is an internal scrap loop within foundries and fabricators. In addition, some end-use scrap is used in primary smelters for temperature control.



As some of our colleagues like to say, "Copper can always be recycled unless it leaves our planet!" And recycling always saves energy and greenhouse gas emissions, though the level of savings can differ. Last but not least, copper produced through the secondary route is indistinguishable from primary copper production. Copper can be recycled repeatedly without loss of quality, and it can even be upcycled under the right conditions.

Further information

https://www.kupferinstitut.de/kupfer-komplett-wiederverwendbar-recycling-entscheidet-ueber-oekobilanz-beim-bauen/ (checked November 26, 2021)

Copper Environmental Profile: https://copperalliance.org/sustainable-copper/about-copper/copper-environmental-profile/ (checked November 26, 2021)

Last update: May 29, 2023

11. Economics of copper

11.1. How many people work in the copper industry?

For a variety of reasons, the employment in the copper industry is somewhat difficult to define:

- Exploration does not necessarily target specific metals, it looks for valuable minerals. Of course, nobody will be displeased to strike copper!
- Copper is seldom mined alone - it comes with a variety of byproducts.
- As one of our members sometimes says, 'half the periodic system passes through a copper smelter', showing again how intertwined copper is with the wider metals industry.
- Finally, copper fabricators and wire & cable companies are very often multi-metal companies, processing copper as well as other materials.
- Most copper companies will work with a mix of employees and on-site long-term contractors.
- Copper mining creates indirect jobs in the industries using copper. E.g. in Chile, it is estimated that for each job in a copper mine, 3.7 jobs are created in other sectors of the economy.

Still, we can try to derive a sensible number using two different approaches which yield approximately the same result:

Member survey

According to the sustainability indicators, the Copper Alliance members surveyed employ about 300,000 people on average per year (note 2). Considering that participating members represent about 40 - 50 percent of global annual copper production, total employment in copper production would be somewhat more than double this figure: **667,000 employees**.

A simple productivity model

An alternative approach is to look at productivity indicators for the various stages of the copper supply chain:

- Mining: we observe numbers in the range of 15 ... 90 tonnes of copper per employee (10% to 90% percentile). Based on figures for 14,9 million tonnes of production (70% of world production), the average works out as 37 tonnes per employee, and the median is 34.
- Smelting and refining: here, we observe 143 ... 430 tonnes of copper per employee, based on 12.2 million tonnes of production with an average of 241 tonnes and a median of 230.
- Fabrication: based on a sample of 17 large fabricators, representing about 25% of global production of fabricated copper products, we find 12.4 employees per ktpa of copper product.

Based on typical production figures in a non-Covid year, we can derive the following employment numbers:

- Mining: 20 million tonnes production -> 540,000 employees (based on average labor productivity)
- Smelting & refining: 24 million tonnes production -> 100,000 employees (based on average labor productivity)
- Fabrication: 24 million tonnes production -> 257,000 employees (based on the median labor productivity)
- Total: 897,000 employees.

> To reconcile both numbers, observe that Copper Alliance's member survey cover only the stages of mining, smelting and refining. Hence the total for these two stages in the simple model - 640,000 employees - is within 5% of the survey figure.

We can conclude that around 900,000 people directly work for the global copper industry from mining to fabrication. Considering the vast amounts of people working in exploration and some specialty sectors not included, we **round it to an even million**.

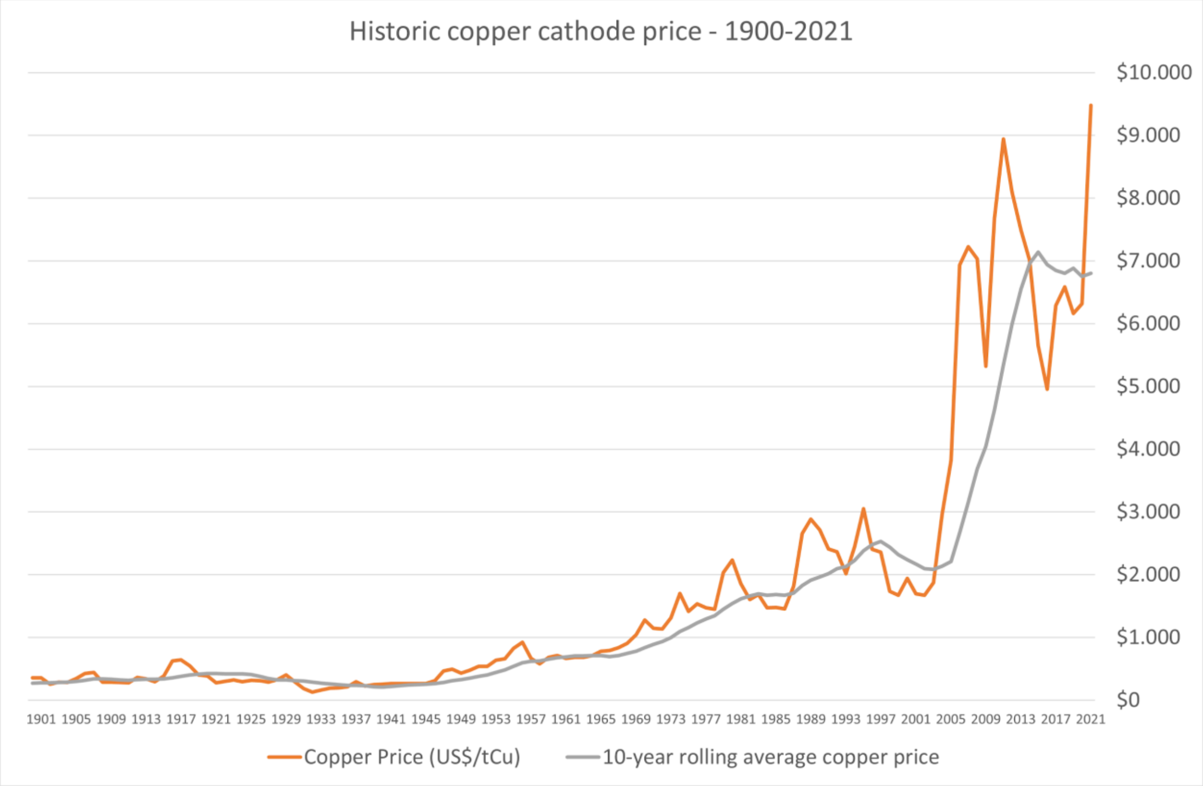
Notes

- The labour productivity indicators have been collected by Copper Alliance research benchmarking 35 mining operations, 18 smelters and refiners and 17 fabricators. For confidentiality reasons, we cannot share the data, but we welcome your own benchmarks and comments on the above indicators.
- The results of the member survey have been reported as part of Copper Alliance's project on sustainability indicators.

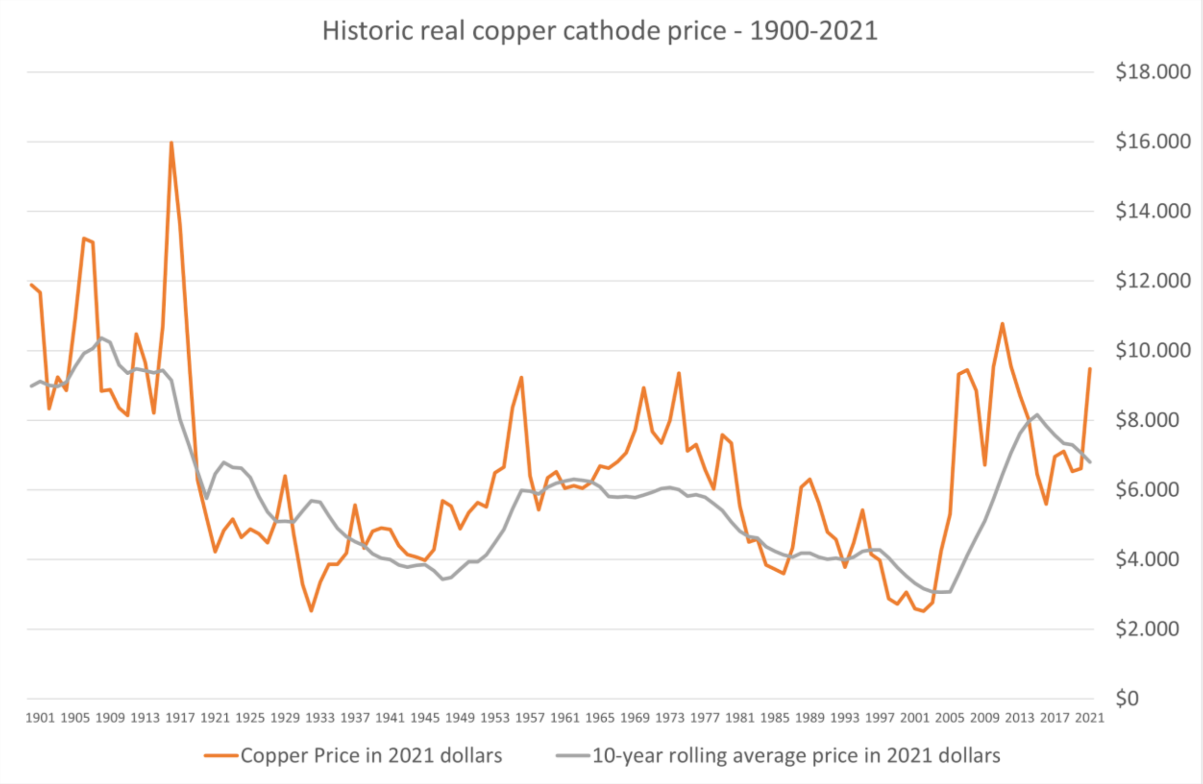
Last update: December 22, 2022

11.2. How has the copper price evolved over the past 121 years?

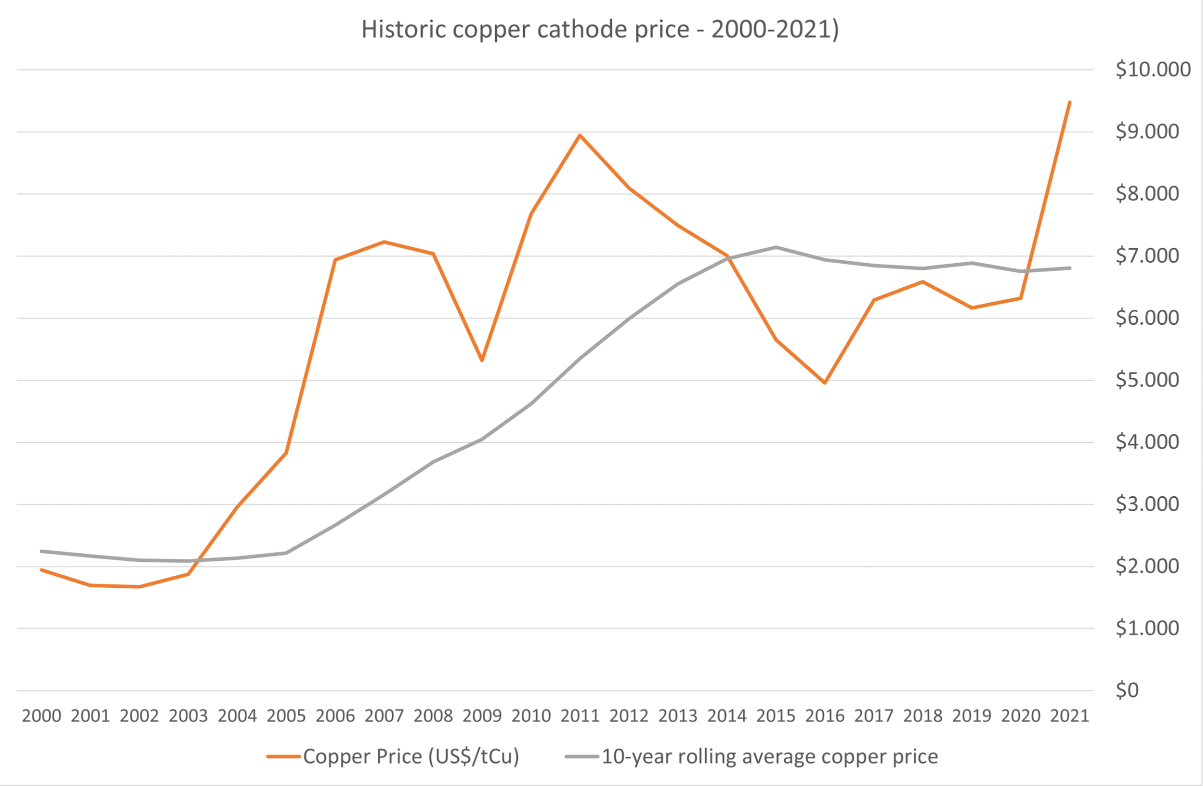
The copper price is set every working day at the London Metal Exchange and at various other exchanges such as New York COMEX or the Shangai exchange. For investment purposes, it is useful to look at average annual prices and even 10-year rolling average prices covering a typical business cycle. The USGS provides a long time series for copper prices since 1900 which allows us to calculate a 10-year rolling average price from 1900.



The price increase from 357 $ in 1909 to 9,477 $ in 2021 (or 270 $ to 6,803 $ for the 10-year averages) looks very significant, but it is well below the cumulative inflation for that period. According to [Fizaine], the copper price even has declined in real terms from the beginning to the end of the 20th century.



When looking at the nominal data for the past 20 years, it shows how a 10-year rolling average copper price provides better information for making long-term investment decisions into copper production.



References

- Data: https://help.copper.fyi/hc/en-us/article_attachments/4456393964178/20220215-HistoricCopperPrice.xlsx
- https://www.usgs.gov/centers/nmic/copper-statistics-and-information
- Fizaine, Floriant, and Xavier Galiegue. 2021. Mineral Resources Economy 1: Context and Issues. John Wiley & Sons.

Last update: February 24, 2022

12. Copper business

12.1. How is the copper price set?

The copper price is set every working day at the London Metal Exchange (LME) and at other exchanges such as the New York Commodity Exchange (COMEX) or the Shanghai exchange. The LME copper price is not a single price, but a variety of price references e.g. for cash, 3 months or December settlement. The LME price is set for a ton of copper cathode - grade A according to standards EN 1978 and ASTM B115. The price is duty unpaid, without VAT or taxes.

The LME operates through three trading platforms: an open-outcry trading floor ("the ring"), an electronic trading platform ("LMEselect") and a vendor network acting on indicative quotes by members over the phone. In the trading pit, LME members meet on business days to define prices that are truly reflective of global supply and demand. The bulk of transaction though takes place through the electronic trading platform. The LME price is used throughout the copper supply chain, upstream to apply a discount to traded intermediary copper products such as concentrate, blister and anodes. It is also used downstream to add production costs to fabricated and wire & cable copper products.

The LME can be used for hedging. LME futures are available daily out to 3 months, weekly out to 6 months and monthly out to 123 months. Cash settled contracts are defined out to 15 months. The contract size for copper is 25 tons. The 3-month prompt for futures is popular and good liquidity for this type of contract can be expected. With so many contract types, the majority of them offer limited liquidity.

The LME is mainly a financial market, i.e. the majority of transactions are settled before their prompt date. Although traders have the possibility to deliver copper or ask delivery of copper from LME warehouses, this is rarely done because the location of a warehouse or a copper shape available may not be convenient. The availability of a copper stock in 610 international storage facilities ensures however price convergence between the physical and financial market. The copper stock levels in LME warehouses are also closely monitored by traders as a barometer of metal markets.

The LME aims for market transparency - microphones and cameras record the trading in the pit. The LME is regulated by the Financial Conduct Authority and by the Bank of England.

Since the LME sets an international reference price that is used by all actors upstream and downstream, copper producers are "price takers" and need a level-playing field to ensure comparability of compliance costs with climate, energy and environmental regulation.

The LME is increasingly committed to responsible sourcing, which has opened up new collaboration paths for Copper Alliance and The Copper Mark.

References

- Guide to the London Metal Exchange - https://www.lme.com/-/media/Files/Education/Online-resources/Brochures/A-Guide-to-the-LME-2022.pdf (checked May 6, 2023)
- Webinar - LME reference prices - https://www.brighttalk.com/webcast/15411/368598 (checked May 6, 2023)

Last update: May 6, 2023

12.2. What is the shareholder structure of the (copper) mining industry?

Based on data from Simply Wall St, we checked the ownership structure of 15 ICA member companies *. These 15 companies were established between 1873 and 1994, manage 660 B$ in assets, generate 504 B$pa in turnover and employ 504,000 people across all their business units (including but not limited to copper). Their combined copper production represents about 50% of global copper mining.

The result:

- Institutional & state ownership: 51%
- General public: 36%
- Employees: 1%
- Individual companies: 12%

As public companies, ICA members publish sustainability reports on average since 2006, leading to 240 sustainability reports cumulatively. Some member companies started sustainability reporting as early as 2001, building more than two decades of experience in this field.

Note

* Companies checked April - May, 2022: Anglo American, Antofagasta, Aurubis, BHP, Boliden, Codelco, Freeport, Glencore, KGHM, Mitsubishi Materials, Rio Tinto, Southern Copper, Sumitomo Metal Mining, Teck Resources, Vale

** The shareholder structure of copper mining companies does not deviate significantly from the typical ownership structure of listed companies, cf table 3 of https://www.oecd.org/corporate/Owners-of-the-Worlds-Listed-Companies.pdf

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Last update: October 28, 2022

13. Copper's environmental profile

13.1. How much energy & carbon emissions are saved when upsizing a cable?

Every conductor in an electrical system has a built-in resistivity. This means that part of the electrical energy that it carries is dissipated as heat and is lost as useful energy. Although the electricity system is rapidly decarbonizing, generating this wasted electrical energy still produces carbon emissions and consequently contributes to global warming.

The answer to the question depends on many factors: the baseline cable to compare to, the high-efficiency solution choosen, the load profile and lifetime, and the greenhouse gas intensity of the electricity mix.

Therefore an example: we compare a 70 mm2 base case with an economically sized cable of 150 mm2:

Emissions for the production of the additional copper

- 150 mm2 – 70 mm2 = 80 mm2 = 0.00008 m3/m difference in cable section
- Additional copper material: 0.00008 m3/m X 8890 kg/m3 = 0.71 kg/m
- Emissions to produce 1 kg of copper: 4.10 kgCO2eq/kgCu
- Emissions for producing additional conductor material in the cable:
- 0.71 kg x 4.10 kgCO2eq/kgCu = 2.9 kg CO2eq/m

Emission savings through energy savings

- Reduced power losses: (1.7241/ 10e8) Ω*m x (200 A)^2 / (80 m2/10e6) = 8.62 W/m
- Reduced energy losses: 8.62 W/m x 3700 hrs/y x 0.65 loading = 20.7 kWh/y*m
- Average carbon intensity EU power generation (2017): 0.230 kg CO2eq/kWh [1]
- 20.7 kWh/y*m x 0.230 kg CO2eq/kWh = 4.8 kg CO2eq
- 4.8 kg CO2eq saved per year per meter of cable

Environmental payback time

2.9 kg CO2eq / 4.8 kg CO2eq = 0.6 y or 7 months

Producing new copper by investing in copper:

- Copper invested: 0.71 kg / m
- Energy saved: 20.7 kWh/m per year
- Over 20 years cable lifetime: 20.7 kWh/m x 20 = 414 kWh/m saved

Energy required to produce 1 kg of Cu: 47 MJ or 13 kWh

-> With the energy saved by investing in 0.71 kg Cu per meter of cable, 31.85 kg of new Cu can be produced (or 45 kg new Cu for 1 kg of Cu)

Moreover, copper cable scrap, which uses copper in its unalloyed form, can be easily recycled into new applications. When used as cooling scrap in a primary smelter, it can be refined using just 0.4 kWh of electricity and 0.1 kg of CO2e emissions per kg of copper.

References

- European Environmental Agency, Greenhouse gas emission intensity of electricity generation in Europe, https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1, accessed April 6, 2022
- International Copper Association, Copper Environmental Profile, March 2018, available from https://copperalliance.org/wp-content/uploads/2021/07/ICA-EnvironmentalProfileHESD-201803-FINAL-LOWRES-1.pdf (accessed April 6, 2022)

Last update: May 3, 2022

13.2. What is the carbon balance of copper use in the energy transition?

Copper use in the energy transition contributes to energy savings, reductions in energy costs as well as reductions in greenhouse gas (GHG) emissions. But what about the costs, energy use and GHG emissions for producing the additional copper? In this article, we focus on the GHG balance. Similar conclusions could be drawn for the energy and cost balance.

When increasing the energy efficiency of cables, GHG savings can be directly attributed to conductors. In cables, copper is the active material producing these savings. Therefore, the resulting savings can be fully attributed to copper, and a GHG balance can be calculated when comparing with copper's environmental profile. In the example in the reference below, this leads to a GHG payback factor of 33. A correction could be calculated for the additional insulation material of the thicker cable, but this effect will be small. Such effort would be better spent to get a more accurate estimate of the duty cycle for that cable, since the use phase represents well over 95% of the GHG footprint.

When improving the energy efficiency in electrical machines such as motors and transformers, there are various design strategies to improve efficiency. Increasing the conductor cross section can be used in addition to using better steels or different designs. Typically, about 30% of energy savings and hence GHG reductions can be attributed to copper. This leads to payback factors in the range of 20 to 300.

Moving to other solutions such as renewables and emobility, these also use more copper in comparison to a fossil power plant of an Internal Combustion Engine (ICE) vehicle. However, these systems need many other materials besides copper. While copper remains the active conductor in the system, there is no agreed methodology to attribute GHG savings to the various materials and processes used. Still, it can be illustrative to calculate how long the system needs to operate to compensate for the emissions related to the additional copper production, in order to provide an indication whether there is enough time to earn back the GHG invested and generate a positive GHG balance. When performing such calculations, we find the following results:

- Renewables (wind or photovoltaics): GHG related to copper production are earned back in 1 - 2 weeks
- Battery Electric Vehicles (BEVs): it takes 2,300 km of driving a BEV compared to a ICE vehicle to earn back the copper's GHG emissions.

The above numbers are based on the Copper Environmental Profile that provides a GHG footprint for a global cathode, based on a mix of primary and secondary material sources as per the production practice in 2018. It doesn't take into account that copper in the above applications is highly recyclable and can start a second or subsequent life after its initial lifetime.

References

- For more details and references on the above numbers, check ECI publication Cu0279 - https://help.leonardo-energy.org/hc/en-us/articles/6572659727890
- For an example of an energy balance calculation, see How much energy & greenhouse gas emissions are saved when upsizing a cable?
- Copper Environmental Profile

Last update: September 22, 2022

13.3. What is the Copper Environmental Profile?

The Copper Environmental Profile (CEP) summarizes the resuts of the International Copper Association's Copper Cathode Life-Cycle Assessment. It covers copper mining, smelting & refining as well as the metallurgical processing of secondary raw material resources (but not their collection, sorting and pre-processing by recyclers and scrap dealers). The CEP takes into account both the pyrometallurgical and hydrometallurgical production routes, representing respectively 80-85% and 15-20% of primary material resources.

The profile has been published in 2018, based on data collected in 2010 - 2013. Data was colleced from International Copper Association's members which include many of the world's largest copper producers and can be deemed representative of ICA member activities but not necessarily of the copper industry's global production of ~ 28 million tonnes at the time of publication. The functional unit for the CEP is 1,000 kg of copper cathode. The 'Big 6' environmental impact indicators are reported. The CEP takes into account credits for co-products such as by-metals in mining, sulfuric acid production in smelting and refining and precious metals production in refining, while accounting for the environmental impacts of these additional processes.

The results indicate, e.g. for the most frequently used impact indicators, that it takes typically 47 GJ and 4.1 tons of CO2equivalent to produce a ton of copper cathode, based on a mix of primary and secondary material resources.

Reference

The Copper Environmental Profile - https://copperalliance.org/sustainable-copper/about-copper/copper-environmental-profile/

Last update: October 23, 2022

14. Copper in society

14.1. What makes copper unique?

The copper sector is highly intertwined with the economy. For example:

- Exploration does not target copper a priori, though striking copper is never bad news.
- Copper is seldom mined alone and comes with a range of by-metals.
- "Half the periodic system passes through a smelter" as one of our members likes to comment. Copper recyclers produce at least 20 different materials.
- Some fabricators and most wire & cable producers are multi-metal companies

However, there are a number of characteristics that help to define a copper sector. What are these characteristics that - in combination - make copper unique? In alphabetical order, these could be:

1. Copper is the best electrical conductor among all metals.
2. Copper has a global ecosystem of 100+ interconnected smelters to manage the flow of primary and secondary raw materials
3. The use of copper is deeply linked to the world's energy system. Copper is key to achieving energy and climate objectives
4. The bronze age marks the first period in history in which metallurgy was used.
5. The mining of copper contributes knowledge to other fields such as geology and civil engineering
6. The copper sector has a geographically dispersed production system over 87 countries. According to World Mining Data 2021, its production is the ninth most dispersed among 60 minerals, and the second among all metals (after gold).
7. Copper is one of the seven metals of antiquity. Copper is probably the first metal ever used by mankind. It has a history of 11 millenia associated a rich culture and folklore.
8. Copper's life-cycle dynamic relates to its use as the conductor of choice in the energy system. Once produced, copper produces significant benefits in use through its long lifetime. And through recycling, copper can go through many lifetimes.
9. Copper is very long-term business. The lifetime of a large-scale mine, from exploration to rebabilitation, can take over a century. Very few processes in the worlds of technology, policy and markets need to take such a deep time perspective.
10. As the third metal, copper is a base metal, but it also displays some characteristics reminiscent of precious metals.
11. Copper's properties make it a high-tech material once it's been mined and refined. At a result, over 80% of copper is used in its unalloyed form. In contrast, well over 90% of other metal use is primarily in alloyed forms.
12. Not only is copper predominantly used in its unalloyed form, it also has electrochemical properties that allow to recycle it without loss of property and it can even be upcycled. In addition, copper smelters recycle over 20 other materials.
13. Considering copper's predominantly sulfide ores, at low grade and copper's high production volumes, copper mining carries a significant risk that needs to be carefully managed.

14. Considering its volume in use, and its semi-precious nature, copper has a large footprint in primary material moved and tailings produced, as well as a significant water footprint.
15. Copper's ubiquity is a characteristic that it probably shares with other materials such as steel, aluminium, chemicals and plastics. However, as a conductor that transports electricity and heat, or as a conductor that produces rotating magnetic fields in electric motors, or generates electricity from rotation in wind turbines, copper is quite literally "the metal that runs the world"

Reference

Brittanica, Bronze Age (accessed March 13, 2022)

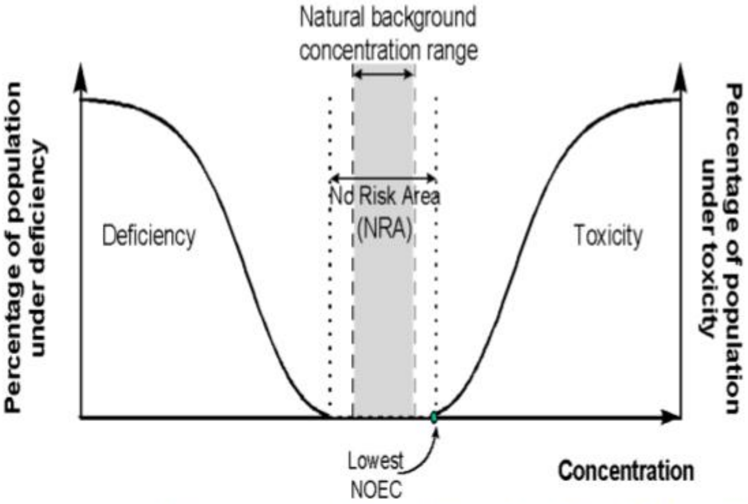
Last update: April 18, 2022

14.2. What's the role of copper in human health?

Copper is an essential trace element vital to the health of all living organisms. Although the amount of copper found in the human body (50–120 milligrams) would fit on the head of a pin, this tiny quantity is essential. Research has revealed that copper is vital for the optimal health of the human body, along with other mineral micronutrients such as iron, calcium and zinc.

Find out more on copper's essentiality for human health [1]:

- The roles of copper in the human body
- Dietary sources of copper
- Copper deficiency and excess diseases (see figure below and [2])
- The essential trio of minerals: Cu, Fe and Zn



Dose-response curve for copper (adapted from Ralph and McArdle, 2001).

References

- Copper's essentiality for human health
- Ralph, A. and McArdle, H. J. 2001. Copper metabolism and requirements in the pregnant mother, her fetus, and children. New York, NY: International Copper Association

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Last update: March 1, 2022

15. Regulatory environment

Content in development

16. The future of copper

16.1. Why does the energy transition need more copper?

The future is bright for copper. The energy transition provides a major driver for new demand, adding potentially 25-50% to the copper stock in use and increasing annual demand by 20-30% depending on the phase of the transition. This observation is well documented in the scientific press, amply discussed in media, but rarely do we hear the question **why** the energy transition needs so much copper. Here are a few reasons that help explain the why:

[1] Small is beautiful when it comes to copper

When it comes to copper use, small machines use relatively more copper than big machines. Take transformers for example: the biggest transformers designed can reach 1,100 Mega-Volt-Ampere, roughly equivalent to the capacity of a large power station. Such transformer will weigh over 400 tons and contain 60 tons of copper. If the copper use per kg of copper would be proportional to its rating, we could expect that a transformer using 60 grams of copper could serve 1,100 volt-ampere of power, i.e. one millionth of its big brother. Actually, it serves only 11 VA or a 100 times less than expected. Put differently, it requires 100 times more copper per unit of power than the largest machines. Similar conclusions can be drawn for rotating machines such as motors and generators.

Hence, smaller units need **more copper per megawatt** (or per unit of power).

[2] Variability leads to more megawatts

In addition to more copper per megawatt, we need more megawatts. A conventional thermal power station may operate e.g. 5,000 to 7,000 hours per year of 8,760 hours. Renewables are weather-dependent. The ratio of their annual energy output and rated power defines their number of full-load-equivalent operating hours, which varies between 900 and 1500 hours for solar photovoltaics to around 4,500 hours of offshore wind power plants. Onshore wind power falls somewhere in-between these two extremes.

Replacing conventional power plants with renewables requires between 1.5 - 8 times more megawatts. In practice, a mix of renewables will be used and **units of power may increase by a factor two to three** for the same amount of energy produced.

[3] Dispersed power needs to be collected by grids

Photovoltaic power systems use lots of land, about 1 ha/MW which can produce 0.9 - 1.5 GWh/year. A large thermal power station of 1 GW running 7,000 hours would be replaced by 5,000 - 7,000 ha of PV power stations, covering 50-70 km2 (or 12,500 - 17,500 acres). All that energy needs to be collected by a wire and cable network. E.g. in photovoltaic power systems, about 25% of copper use is in the modules and 75% in the wiring. And when it comes to wind power systems, each offshore wind farm leads to a new copper demand of a few hundred tons in the cabling.

Hence, there is at least as much **copper in connections** than there is in equipment.

[4] Variability also leads to a need for redundancy and the use of combined solutions

Electricity needs to be delivered to customers at the right time. The balancing of supply and demand in a near 100% renewable electricity system requires a carefully designed mix of flexibility on the supply side, flexibility on the demand side, grid level integration and an appropriate use of energy storage. All these additional systems require copper to a varying extent.

Hence, deep integration of renewables leads to additional **hardware and redundancy solutions requiring copper**. For example, batteries currently use 0.4 kg of copper per kWh; smart buildings use 10 to 30% more copper in their electrical installations.

[5] The energy transition is electricity-intensive

The rapid decarbonisation of the electricity system, in combination with the unsurpassed end-use efficiency of electricity drives electrification in the energy transition, i.e.:

- the electrification in OECD economies of heating & cooling in buildings and of passenger transport;
- the indirect electrification of hard-to-decarbonise sectors such as the process industry, long-haul transport and seasonal storage through e-fuels and green hydrogen.
- the electrification of rural and peri-urban communities in developing economies for energy access.

Over the past century, we observed a **strong relation between copper and electricity use**. Going forward, this link is particularly apparent in the area of emobility.

[6] Energy efficiency further adds to copper demand

In cables, transformers and rotating machines, **losses can be reduced economically through using more copper**. This is somewhat a secondary effect compared to the above-mentioned trends for renewables, energy flexibility and electrification but it is significant, and moreover, energy efficiency can partially offset the additional electricity use due to electrification and improve the cost-effectiveness of the energy transition, making it more acceptable for energy users.

High efficiency motors and transformers use typically 20% more copper. Upsizing a cable requires 50% more copper.

Last update: July 27, 2021

16.2. How has the copper industry evolved over the past decades?

Copper is one of the oldest industries, yet it keeps evolving. Hereby a few trends observed over the past decades:

Growth: from 12 Mtpa in 1995 at a 10-year average price of 2,400 $/t to 25 Mtpa in 2020 at 6,800 $/t, the copper industry has grown from 29 B$ to 170 B$ or 7.3% per year. Volume growth represented 3% per year, while nominal price increased by 4.3% per year. As a result, copper production has grown from 0.1% nominal world GDP in 1995 to currently 0.2%.

Complexity of raw materials: ore grades are gradually decreasing and the complexity of concentrates is increasing. The same trend is observed for secondary raw materials. As a result, the industry evolves into an ever more complex metallurgy to extract copper and other valuable materials from these resource streams.

Integration: copper processing increasingly becomes a team effort. A network of interconnected, integrated smelters is developing.

Multi-metal: copper companies produce a multitude of metals. Over 20 materials can come out of a smelter.

Regulatory environment: regulations surrounding copper mining, smelting and refining are proliferating. The 2021 edition of ICSG's "Survey of Regulatory Developments Affecting Copper" has 369 entries.

Society's expectations: demands for sustainable operations and ESG performance are rising. The times are long past when mining districts were sacrifice zones for a global market.

Innovation: the copper sector continually innovates and reinvents itself to process increasingly complex material streams with less impact. Modern mines are a break from the past in terms of operational safety, water & energy use, automation, tailings management, ... See www.modernmine.org.

Markets: demand is shifting as well. Conductivity applications represent an ever greater portion of copper demand (currently 70%, not including thermal applications). The energy transition has become central to policy making, and electification offers a major pathway forward.

China: as for many commodities, the copper market is dominated by China who hosts half of the global smelting & refining capacity. China's policies on copper, e.g. on scrap trade, have major implications for the rest of the world.

Risk: considering the variation in environmental, social and governance concerns across geographies, a framework for resource governance has yet to emerge, and risks for operators are increasing. It takes close to 20 years to develop a new mine from exploration to first production. As the mining industry is capital-intensive, risk is a major cost factor.

Copper in the spotlight: compared to the 90s and the early part of this century, copper is no longer "the hidden metal". Copper is regularly covered in reports from regulatory agencies, featured in the scientific press and increasingly finding its way into popular culture.

Further reading

Processing of Complex Materials in the Copper Industry: Challenges and Opportunities Ahead - https://link.springer.com/article/10.1007/s11837-020-04255-9 (accessed June 7, 2022)

Extractive Metallurgy of Copper, 6th edition - https://www.elsevier.com/books/extractive-metallurgy-of-copper/schlesinger/978-0-12-821875-4 (accessed June 7, 2022)

Last update: September 20, 2022

17. Key numbers

17.1. Where is copper produced?

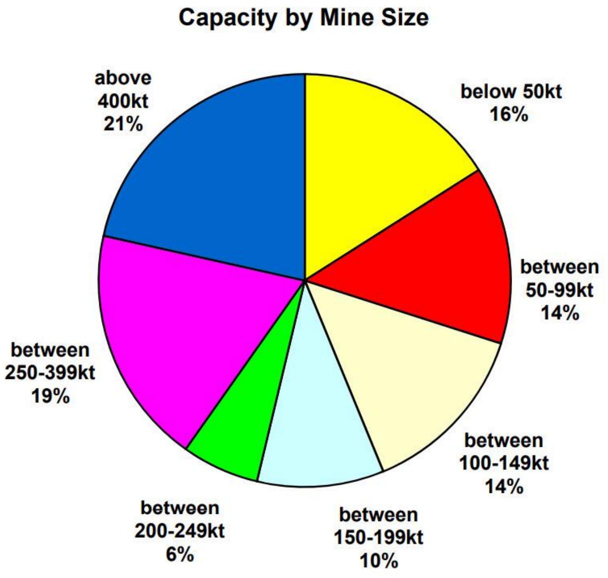
According to ICSG's Directory of Copper Mines and Plants, 2021 edition, the global copper sector consists of:

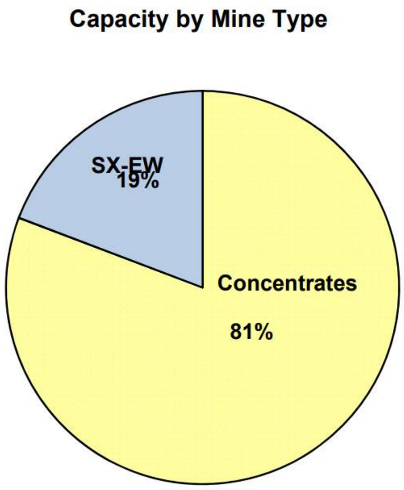
- 480 mines in 55 countries
- 125 smelters in 40 countries
- 230 refineries in 45 countries (of which 115 SX-EW facilities in 25 countries).

In total, copper facilities operate in 78 countries spread over the world's six continents. A further 355 mining, smelting or refining projects are in various stages of development.

In addition, there are thousands of fabricators and close to 10,000 wire & cable producers transforming copper into final products with 116 end-uses. E.g. ICSG's Directory of Fabricators lists ~ 2,000 fabricators operating in 87 countries.

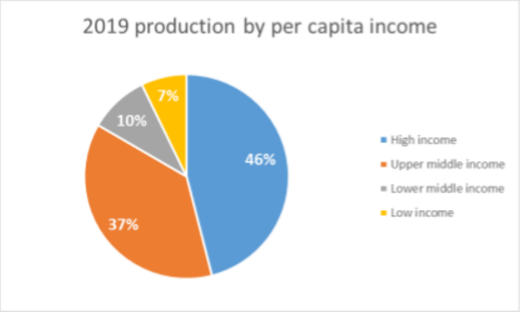
Copper production capacity is concentrated in larger mines cf the ICSG directory. The 20 largest mines represent 35% of production capacity.



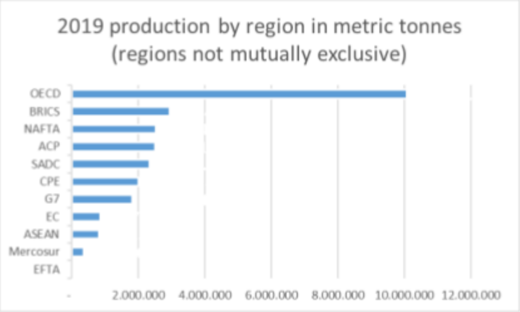


WMD proposes a subdivision of copper production by development status, per capita income, political stability and geographic region:

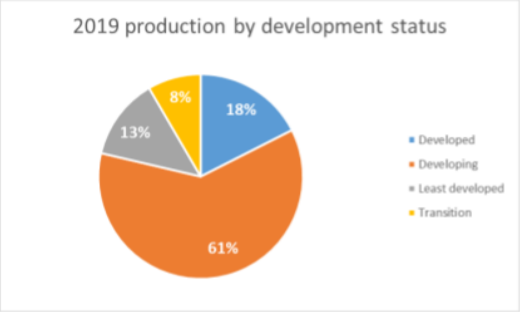
Where is copper produced?



2019 production by per capita income



2019 production by region in metric tonnes (regions not mutually exclusive)



2019 production by development status

The Herfindahl–Hirschman Index measures market concentration [4]. It rates markets on a scale up to 10,000 (fully concentrated) and approaches zero for markets with perfect competition. WMD calculates the HHI for commodities based on the geographic dispersion of their production. Though not strictly an intended use of the HHI, it provides a measure for the level of concentration.

Copper's HHI is 1,175, the 9th best figure among 64 commodities. Copper scores better than its competing materials or than some of the mineral fuels that it substitutes through renewables, energy efficiency or electrification.

References

- ICSG Directory of Copper Mines and Plants 2021 Edition - https://icsg.org/wp-content/uploads/2021/07/Directory-of-Mines-Plants-SAMPLE-copy.pdf accessed January 31, 2022)
- ICSG Directory of Copper and Copper Alloy Fabricators (first use) - https://icsg.org/wp-content/uploads/2021/07/Semis-Directory-Description.pdf accessed January 31, 2022
- World Mining Data - 2021 edition (accessed Jan 31, 2022) - https://www.world-mining-data.info/ accessed January 31, 2022
- https://www.justice.gov/atr/herfindahl-hirschman-index accessed January 31, 2022

Last update: July 1, 2022

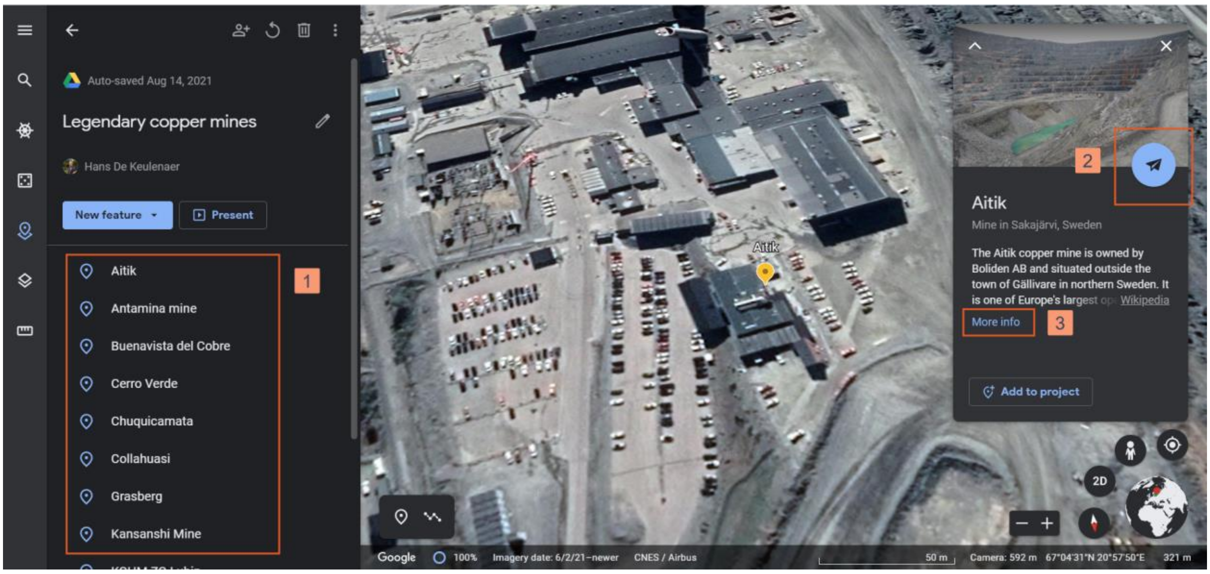
18. The chapter of tens

18.1. Show me a few copper mines

According to ICSG's database, there are about 500 copper mines of varying size in operation. Some of the larger copper mines can be easily spotted through Google Earth and you can visit them virtually from the comfort of your desktop. This is a great way to get a feeling for the challenges and diversity of copper mines across the globe.

Click http://copper.fyi/cuminetour

1. Select a mine of interest (or 'present' to browse through the sequence)
2. Click the plane to take a virtual flight
3. Click for more information



The Aitik copper mine is owned by Boliden AB and situated outside the town of Gällivare in northern Sweden. It is one of Europe's largest op

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A more complete listing of copper production sites, covering mining, smelting, refining and recycling can be found here: https://copperalliance.org/sustainable-copper/copper-pathways-map/

Updated September 23, 2021

18.2. What are some examples of copper mine rehabilitation?

Copper is a very long-term business and most of the large-scale copper mines of the 20th century are still in operation. But copper has an even longer history. Hereby an overview of rehabilitated copper mines, sometimes from a distant past. The first 12 cases come from reference [1], and cases 13-14 can be found in [2]. From bullet 16 onwards, we list recent examples of restoration efforts from ICA members.

1. UK: Parys Mountain, Anglessey - an area where copper was mined since the Roman era, and which was the largest copper mine in the world in the 18th century. Now a hiking area. [1 - p45] In the laboratory, metal-tolerant plant species have been developed that can be used in restoration projects. [1 - p71]
2. Chile: Sewell - copper mining town built high up in the Andes in the early 20th century, now a Unesco World Heritage Site. [1 - p50]
3. UK: Cornwall - mining region which supplied half of the world's copper and tin in the 19th century, now its 56 sites classified as Unesco World Heritage. [1 - p53]
4. US: Bingham - sustainable housing, LEED certified, in the buffer zone.
5. Germany: Braubach - a 14th century copper & silver mine transformed into a battery recycling plant. [1 - p58]
6. Australia: Woodlawn - bioreactor landfill to process biological waste. [1 - p63]
7. UK: Gwennap Pit - mining subsidence converted into an amfitheatre, used as a place of worship. [1 - p66]
8. Canada: Flin Flon - plant-based biopharmaceutical production in an underground copper & zinc mine. [1 - p79]
9. Finland: Pyhasalmi - sauna at 1,440 m depth in an underground copper & zinc mine. [1 - p79]. Also home to the Callio project - https://callio.info/ and https://calliolab.com/
10. Italy: Valpelline - cheese production in an old copper mine. [1 - p84]
11. Sweden: Stekenjokk - reindeer breeding at an old copper, zinc and silver mine. [1 - p100]
12. Tasmania: Mount Lyell - moonscape hiking area. [1 - p105]
13. US: Flambeau mine - from copper mine to nature trail. [2 - p15]
14. Canada: Vancouver Island - underwater tailings placement for a copper mine. [2 - p16]
15. US: Bisbee - from mining camp to quirky tourist destination - https://www.azfamily.com/2022/06/09/bisbee-queen-copper-camps/
16. Sweden: restoring open pit mines - http://www.boliden.com/Sustainability/Case-studies/Gillervattnet-reclamation-project/
17. US: creating nature reserves - http://www.kennecott.com/inland-sea-shorebird-reserve
18. Mongolia: protecting the desert - http://www.nature.org/about-us/working-with-companies/companies-we-work-with/rio-tinto-case-study.xml
19. Poland: restoring water quality and woodland - https://kghm.com/en/sustainable-development/environment/mine-reclamation

References

- Georgina Pearman, 101 Things to do with a Hole in the Ground, Post Mining Alliance, 2009
- Mary Poulton, University of Arizona, 102 Things to do with a Hole in the Ground, https://www.nationalacademies.org/event/04-10-2017/docs/DB3695EDFD316F1BB348A6E54E7BA99BC3897B397814 (visited February 9, 2022)
- Copper Alliance, Sustainable Mining With A Long-Term Vision, https://copperalliance.org/resource/sustainable-mining-with-a-long-term-vision/ (accessed March 16, 2022)

Last update: June 10, 2022

18.3. Which historic copper sites are open to the public?

Copper as a tourist destination?

Here are some sites to learn more about copper:

The **Allihies Copper Mine Museum** in Cork, Ireland, on copper mining at the beginning of the industrial revolution:
https://acmm.ie/

The **Arizona Copper Art Museum** in Clarkdale, AZ (US), "connecting copper to world legends and art":
https://www.copperartmuseum.com/

The **Ashio Copper Mine** operated since the time of the Shoguns, located near the city of Nikko (Japan):
https://www.city.nikko.lg.jp/asiokankou/kankou/ashio/taiken/douzan.html

https://japannews.yomiuri.co.jp/features/japan-focus/20221116-71091/

Codelco's Virtual Museum looking 50 years back on forward on copper's (hi)story: https://museocodelco.cl/

The **Copper Museum** by Lafarga including a tour of an operational copper plant near Barcelona (Spain): https://www.lafarga.es/en/the-group/the-copper-museum/introduction

Falu Gruva in Falun (Sweden) with a thousand years of history and a UNESCO World Heritage Site: https://www.falugruva.se/en/

The **Kapunda Mine Trail and Site** in Adelaide Hills Australia: https://www.lightcountry.com.au/atdwproduct/kapunda-mine-trail-and-site-attraction-kapunda

The **Kennecott Visitor Center** in Kennecott, AK (US), definitely off the beaten track.
https://www.nps.gov/wrst/planyourvisit/kennecott-visitor-center.htm

https://www.cnet.com/culture/ghosts-of-kennecott-exploring-an-abandoned-copper-mine-in-alaska/

The **Mineral Museum of the Great Lakes Region** in Houghton, MI (US), displaying a.o. the world's largest known block of native copper weighing 19 tonnes (about 2 cubic meters):
https://museum.mtu.edu/visit

The **Museo Minero de Tierra Amarilla** in the Atacama Region (Chile) "aspires to be a place for reflection and appreciation of representative aspects of the economic, historical and cultural reality of mining communities".
https://museominero.cl

The **Queen Mine Tour** in Bisbee, AZ (US): visit a closed underground copper mine: https://www.queenminetour.com/

A day trip to the **Sewell Mining Town** in Machali (Chile) - a day trip out of Santiago to visit a UNESCO World Heritage Site: https://whc.unesco.org/en/list/1214/

A historic **Stolzembourg copper mine** that operated 500 years (Luxembourg): https://www.stolzembourg.lu/kupfermine/

Sygun copper mine in Beddgelert (UK) - an underground copper mine in Wales:

http://www.syguncoppermine.co.uk/

The **World Museum of Mining** in Butte, MT (US): https://miningmuseum.org/

Last update: July 27, 2023

19. Copper topics

No content yet.

20. Organisations supporting the copper industry

20.1. What is International Copper Association?

> *"As global issues such as energy, climate change and health become more urgent, copper plays an important role in almost every industry."*

The International Copper Association, Ltd. (ICA) brings together the global copper industry to develop and defend markets for copper and to make a positive contribution to society's sustainable-development goals.

https://copperalliance.org/about-ica/about-ica-and-copper-alliance/

See also ICA's latest annual report:

https://copperalliance.org/wp-content/uploads/2022/03/ICA-AnnualReport2021-Final-Single.pdf

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Last update: May 12, 2023

20.2. What is the International Wrought Copper Council (IWCC)?

The International Wrought Copper Council (IWCC) is the representative industry supported organisation for the global copper and copper alloy semis-manufacturing industry. The IWCC has members in North America and South America, Europe, Africa, South Asia, South East Asia, the Far East, China and Japan. The IWCC is established to promote commerce within the Industry by the encouragement of lawful co-operation within the Industry; the exchange of information; and the provision of networking opportunities.

More information: http://www.coppercouncil.org/

Last update: October 28, 2021

20.3. What is the International Copper Study Group (ICSG)?

The International Copper Study Group (ICSG) was established in 1992 in order to promote international co-operation on issues concerning copper by improving the information available on the international copper economy and by providing a forum for intergovernmental consultations on copper. In order to fulfil its mandate, the Study Group has three objectives:

Noteworthy activities from the ICSG:

- Increasing market transparency and promoting an exchange of information on production, consumption, stocks, trade, and prices of copper including the forecasting of production and usage and the assessing of the present and future capacities of copper mines, smelters and refineries.
- Promoting international cooperation on matters related to copper, such as health and the environment, research, technology transfer, regulations, and trade.
- Providing a global forum where industry and governments can meet and discuss common problems/objectives. The ICSG is the only intergovernmental forum solely dedicated to copper. The meetings of the Study Group are open to government members, their industry advisors, and invited observers.

More information: http://www.icsg.org/

Last update: February 28, 2022

20.4. What is the Copper Development Association Africa?

The CDAA has represented the local copper industry in southern Africa since 1962, and, on behalf of its members, is committed to promoting and expanding the use of copper and copper alloys throughout Africa.

More information at https://www.copper.co.za/

Last update: November 16, 2021

20.5. What is Cochilco?

The Chilean Copper Commission (Cochilco) is a highly specialized government organisation. Since 1976, it advises the Government on matters related to the production of copper and its by-products, in addition to all metallic and non-metallic mineral substances, except for coal and hydrocarbons. In addition, it safeguards the interests of Chile in its mining companies through the supervision and evaluation of their management and investments; and it advises the Ministries of Finance and Mining in the preparation and monitoring of their budgets.

National and international mining organisations recognize Cochilco as a reliable source of information that provides timely diagnoses of the main problems of the sector and generates proposals for policies, strategies and actions to solve them.

More information at https://www.cochilco.cl/

Last update: November 16, 2021

20.6. What are some of the milestones of copper industry association?

1921	The Copper & Brass Research Association (CABRA) formed to promote copper use in the post-war US economy
1927	Foundation of Deutsches Kupferinstitut (DKI) in Berlin
1953	Foundation of the "International Wrought Copper Council" (IWCC)
1959	"Copper Products Development Association" formed in New York
1961	Name of the "Copper Products Development Association" changed to "International Copper Research Association" INCRA works in parallel in Europe with CIDEC (Conseil International pour le Développement du Cuivre, a producer body founding CDAs outside North America) INCRA London office established
1963	Foundation of Copper Development Association Inc to "bridge the gap between companies that mined copper, fabricated copper products, or marketed copper and copper alloys to those that produce a myriad of applications'"
1969	INCRA European office split. UK office (UK & Scandinavia) moved with CIDEC (technical information) to share offices with CDA UK CIDEC moved to Geneva. INCRA office established with CIDEC to cover mainland Europe
1974	INCRA office Geneva closed. All INCRA European activities consolidated in UK CIDEC closed
1989	INCRA reformed as ICA. Market promotion (global) run from UK office
1992	ICA market promotion split into building construction (run from UK office) and electrical (run from New York)
1995	ICA establishes the Bejing office to extend its copper promotion activities to China

1996	Establishment of European Copper Institute and re-organisation of ICA along regional lines
2002	DKI celebrates its 75th anniversary
2004	ECI wins EU Commission award for its Leonardo Power Quality Initiative as European best practice in vocational training
	DKI issues for the first time its Innovationspreis Kupfer
2006	ECI launches the Leonardo ENERGY Initiative, the "Global Community for Sustainable Energy Professionals" to accelerate the energy transition
2008	ECI completes the voluntary risk assessment and establishes the Reach Consortium
2012	Development of the Cu - Copper Alliance brand of common identity for the copper network
2017	Public Affairs function added to ICA
2018	ICA celebrates 20 years of partnership with the United Nations, especially on SDG7 - affordable & clean energy
2020	Launch of The Copper Mark, copper's assurance framework to promote responsible production practices and demonstrate the copper industry’s commitment to the green transition

Besides the above list of industry organisations, the International Copper Study Group was established in 1992 to promote international co-operation on issues concerning copper. Unlike the above-mentioned industry organisations, the ICSG is an intergovernmental organisation between 24 member countries and the European Union.

References

- History of DKI - https://www.kupferinstitut.de/ueber-uns/geschichte/
- CDA: Celebrating 40 Years of Service - https://www.copper.org/about/anniversary/page1.html

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Last update: March 1, 2022

20.7. Copper industry initiatives

20.7.1. What is the end-use dataset?

As with most primary industries, statistics on copper production are readily available, while accurate demand statistics are much harder to find.

This is why the International Copper Association (ICA), in close collaboration with the International Wrought Copper Council, has been developing the copper end-use dataset since 2006. The dataset provides a perspective on how 18 of the most common copper products are used in 16 end-use markets worldwide. Within this combination of products and markets, there are 288 total possible uses for copper products, although only the most common 116 uses are explored in the dataset.

Covering 116 product/end-use combinations, in 15 geographies over nine years, the dataset provides a comprehensive 15,660 datapoints on copper use.

The full dataset is an ICA member-only service. An annual summary covering global copper use is publicly available from the Copper Alliance website: https://copperalliance.org/wp-content/uploads/2021/09/Global-2021-Semis-End-Use-Data-Set.xlsx

The end-use dataset is one of ICA's flagship intelligence projects. It demonstrates how interwoven copper is with economic activities, to the extent that analysts regularly refer to copper demand as a barometer of economic health ("Dr Copper").

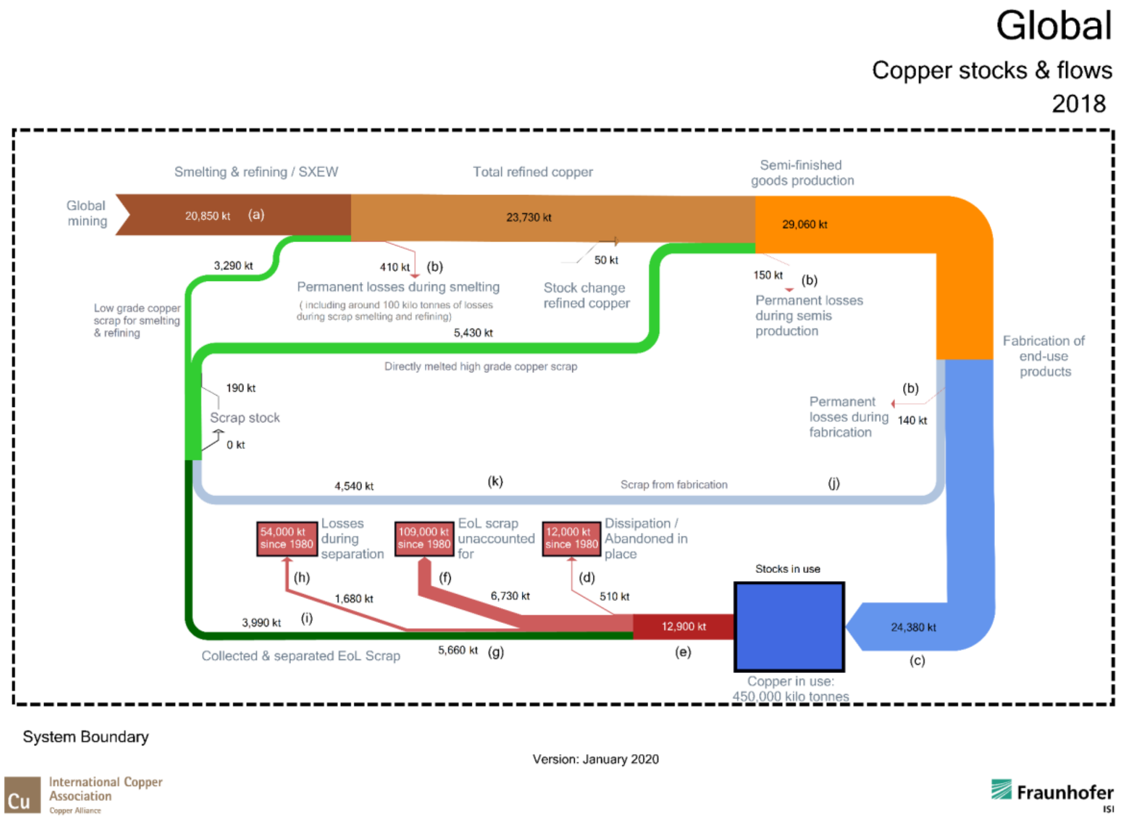
Mega trends, such as the energy transition, digitalisation and sustainable development, are expected to result in significant demand growth for copper. A global copper industry of 500 copper mines, 200 smelters/refiners and thousands of fabricators is in place to meet these expectations.

Last update: October 12, 2022

20.7.2. What is the copper flow model?

The copper flow model has been developed by Fraunhofer ISI for Copper Alliance since 2012. It aims to map the copper flows in the global economy as well as the stocks in use through material flow analysis (MFA). The copper flow project adopts a dynamic approach for MFA. The model goes back to 1910 and builds up the copper stock in use by combining supply side and end-use statistics. Although there is no independent way to check all results, and missing data points are filled by extrapolation and inference, the model is unique in that it makes full use of the best available industry statistics and accounts for all relevant flows -- nothing disappears under the carpet.

The dynamic approach allows to model the amount of copper that becomes available at the end-of-life, a parameter that would be difficult to estimate otherwise. Based on this, a series of recycling indicators can be estimated.



Some topline results from the model (as of 2018):

- Copper stock in use globally: 450 million tonnes.
- Copper stock in use in China: 103 million tonnes.
- Copper stock in use in EU: 82 million tonnes.
- Copper stock in use in Japan: 27 million tonnes.
- Copper stock in use in Latin America: 28 million tonnes.
- Copper stock in use in North America: 86 million tonnes.

- (Calculated) copper stock in use in the rest of the world: 124 million tonnes.

References

- Glöser, Simon, Marcel Soulier, and Luis A. Tercero Espinoza. 2013. “Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation.” Environmental Science & Technology 47 (12): 6564–72. https://pubs.acs.org/doi/10.1021/es400069b
- Soulier, Marcel, Matthias Pfaff, Daniel Goldmann, Rainer Walz, Yong Geng, Ling Zhang, and Luis A. Tercero Espinoza. 2018. “The Chinese Copper Cycle: Tracing Copper through the Economy with Dynamic Substance Flow and Input-Output Analysis.” Journal of Cleaner Production 195 (September): 435–47. https://doi.org/10.1016/j.jclepro.2018.04.243
- Soulier, Marcel, Simon Glöser-Chahoud, Daniel Goldmann, and Luis A. Tercero Espinoza. 2018. “Dynamic Analysis of European Copper Flows.” Resources, Conservation and Recycling 129 (February): 143–52. https://doi.org/10.1016/j.resconrec.2017.10.013

Last update: March 16, 2022

20.7.3. What is the Zero Emission Mine of the Future initiative?

The Zero Emission Copper Mine Of The Future is a global project to create cleaner, greener & smarter copper mines.

The project started in 2020 and has so far produced two reports with The Warren Center:

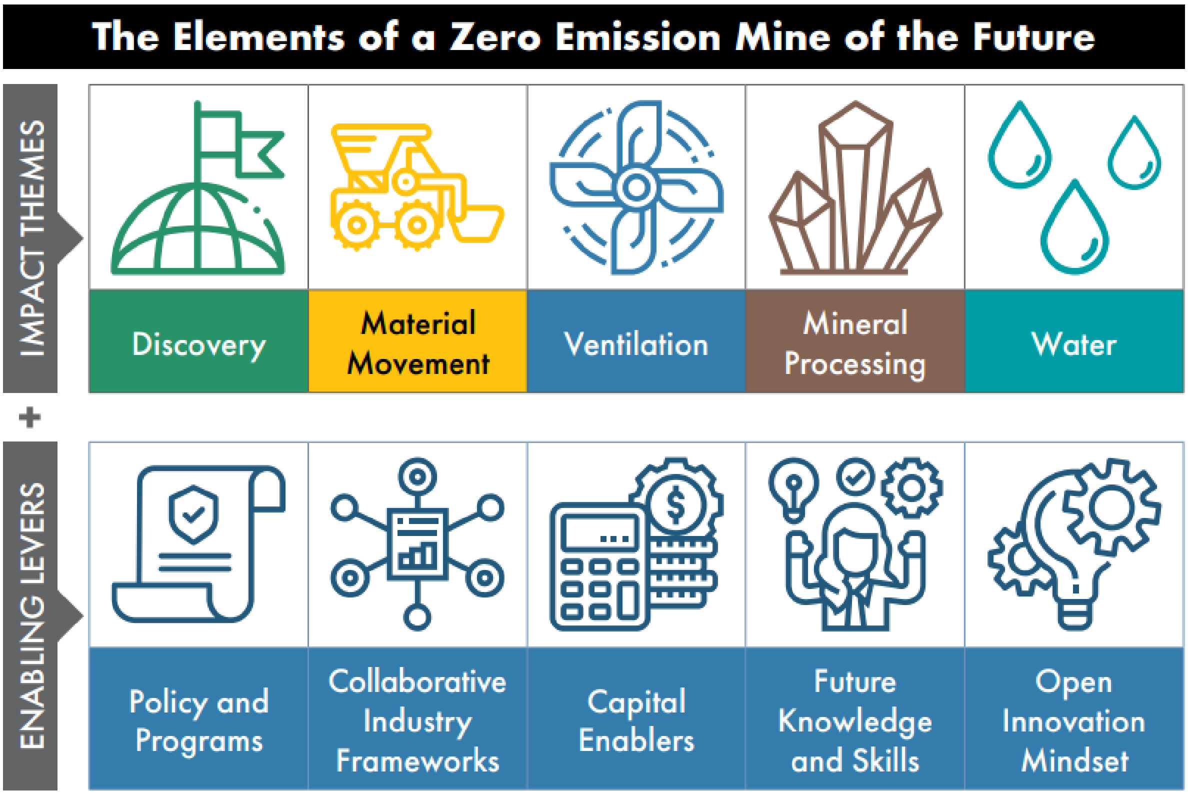
1. An overview report "Zero Emission Copper Mine of the Future" (2020)
2. The Water Report (2021)
3. Material Movement Report (2022)

Three more Roadmaps are planned on discovery, ventilation, and mineral processing covering a total of five impact themes.

The overview report the five impact themes for the Zero Emission Copper Mine of the Future as well as five enabling levers, which are developed for three horizons:

1. Horizon 1: current operations and incremental improvements
2. Horizon 2: asset upgrades and capital expenses
3. Horizon 3: future operations

Pull quote: "A zero-emission copper mine of the future will be significantly different from the current copper mining system and will require fundamental changes in how energy is consumed, sourced and abated." ~ The Warren Center



The Water Report addresses water management in mining operations and works out six innovation themes along the three horizons:

1. Base line measurement

2. Dewatering
3. Desalination
4. Operational water use
5. Tailings
6. End use and reuse

The Materials Movement Report introduces one of minings foundational processes and introduces five innovation themes along three horizons:

1. Fragmentation
2. Convey and sort
3. Haulage
4. Dispose and reuse
5. Digital and automation

More information: https://copper.com.au/about/projects/zero-emission-copper-mine-of-the-future/

Last update: March 17, 2023

21. Further readings

21.1. Copper glossary

Terminology provides a common language for an industry to discuss matters internally as well as with its suppliers, customers and regulators. Copper's glossary covers the material streams, metallurgy, technology, production systems and products surrounding the copper value circle. Hereby a few sources of copper terminology:

A short glossary of copper terms is available on this website:

Glossary of terms

For a more extensive glossary, refer to Dr Langner's website:

http://www.understanding-copper.com/glossary.php (accessed August 18, 2023)

To support its statistical program, the International Copper Study Group provides a series of definitions and descriptions for copper-based products:

https://icsg.org/wp-content/uploads/2021/12/Definitions.pdf (accessed August 18, 2023)

Various glossaries are available on the website of the Copper Development Association:

https://copper.org/search.php?q=glossary&submit=Search (accessed August 18, 2023)

Last update: August 18, 2023

21.2. What textbooks are available on copper?

The following books provide a broad overview of the copper sector from various perspectives:

Understanding Copper: Technologies, Markets, Business (Bernd Langner)

Written in 2011 by a retired senior executive with a long career in copper, this book provides an inside view of copper's value circle, including business, economic, environmental and technological aspects.

http://www.understanding-copper.com/

Copper: Its Trade, Manufacture, Use, and Environmental Status (Konrad Kundig ed)

Edited in 1999 by a former Copper Alliance colleague, this is a textbook covering copper's properties, its manufacturing and applications. It also includes chapters on trade and environment which are probably rather dated by now. The book is no longer in print, but available through many libraries.

https://books.google.be/books/about/Copper.html?id=vaJTAAAAMAAJ&redir_esc=y

Boom, Bust, Boom: A Story about Copper, the Metal that runs the World (Bill Carter)

Written in 2012 by an environmental activist and documentary maker, this book addresses a central question how to reconcile copper's major contribution to the world economy - nothing less than "the metal that runs the world" - with the impacts of copper production? In a way, it is an alternative Copper Story.

https://www.billcarter.cc/boom-bust-boom

Extractive Metallurgy of Copper (Mark Schlesinger et al)

An award-winning, academic reference textbook, in development and print since four decades:

https://www.sciencedirect.com/book/9780080967899/extractive-metallurgy-of-copper

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Last update: June 1, 2022

22. Copper & other metals

22.1. What does all metal mining have in common?

While copper is unique, its production also shares many aspects with other metals:

1. New mining projects are subject to extensive consultations with local communities and negotiations with local and national governments.
2. New mines need a long time to start up: depending on the the regulatory environment and how stakeholder consultations go, typical start-up times vary between 5 and 15 years.
3. Ore grades are generally declining.
4. Mining costs are going up - e.g. a hauling vehicle in Chiquicamata needs 3 hours from the bottom of the pit to the concentrator plant. With changing market conditions, a mining project is a continual business decision.
5. Mining projects are capital-intensive. They also have high operational costs (labour, energy, water).
6. Mining is risky business, and these risks lead to a higher cost of capital.
7. For underground mining, the management of heat, humidity and water in a space-constrained environment is a constant struggle.
8. Most mines need some level of concentration of materials, and in any case, management of both hazardous & non-hazardous waste.
9. All mining is looking for reuse of its waste rock in building construction and civil engineering. The circularity potential from mining is not yet well understood and largely untapped.
10. Water use and discharge - in some cases, risk of pollution of nearby rivers or lakes.
11. Besides water, mining requires energy and explosives.
12. During a mining operation, a certain on-site loss of biodiversity might be unavoidable. There are mitigation, offsetting and other possibilities open to restore biodiversity and achieve no-net-loss.
13. Mining changes landscapes in an often irreversible manner. A mining project includes a rehabilitation plan repurpose an area after a mining project has been completed. Some very creative uses for mines have been found after closure [2].
14. Location: most metal mining takes in remote places that are far away from where mining products are used.

References

- KPMG, Global Mining Risk Survey Report 2021, https://home.kpmg/xx/en/home/insights/2021/02/risks-and-opportunities-for-mining.html (accessed March 14, 2022)
- Georgine Pearman, 101 Things to Do with a Hole in the Ground, https://www.worldcat.org/title/101-things-to-do-with-a-hole-in-the-ground/oclc/1026212499 (accessed March 14, 2022)

Last Update: April 11, 2022