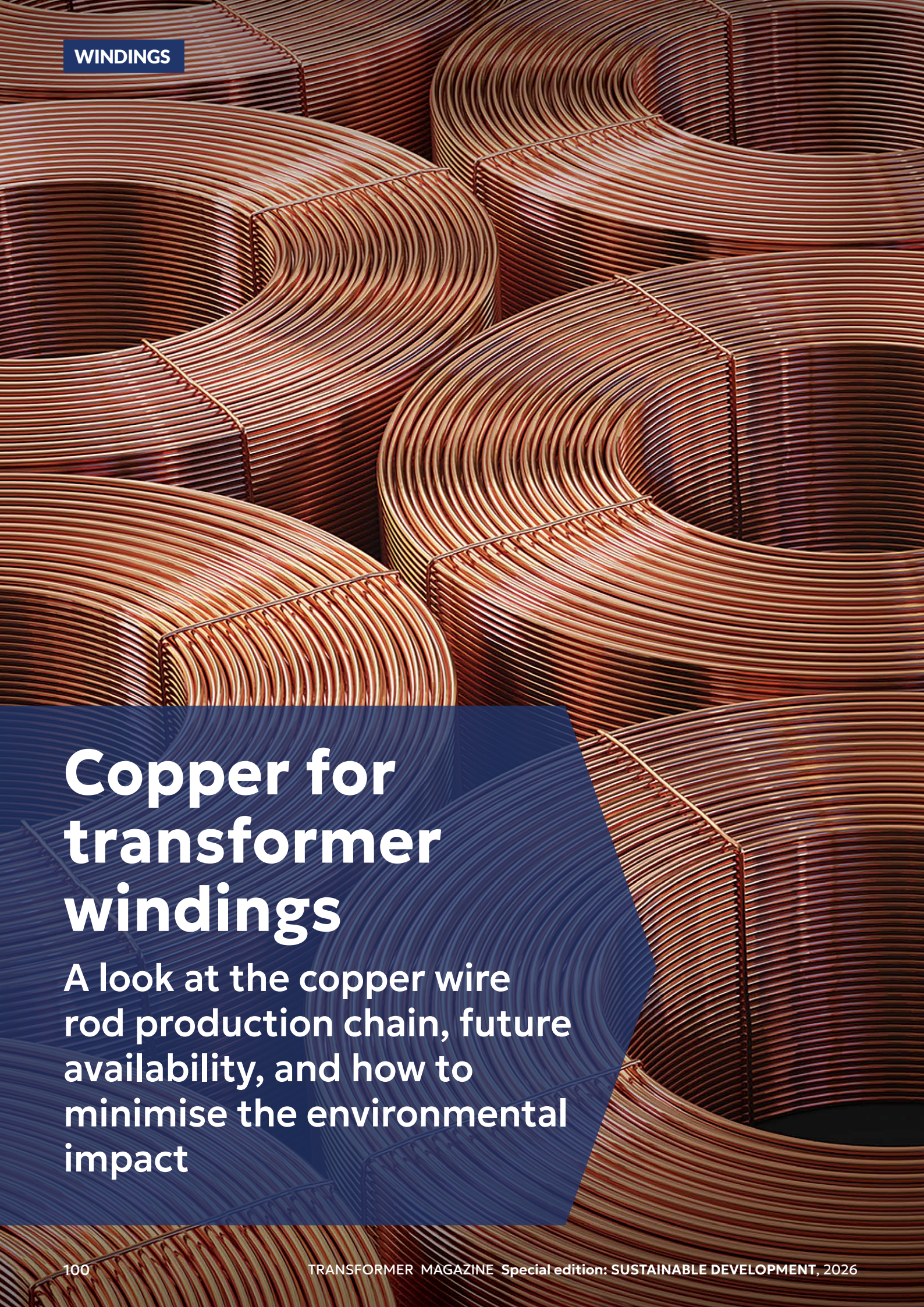

Copper for transformer windings

A look at the copper wire rod production chain, future availability, and how to minimise the environmental impact

Bruno De Wachter, Fernando Nuño



ABSTRACT

Transformer manufacturing depends heavily on globally traded raw materials — including electrical steel, copper, and aluminium — raising critical questions about whether supplies can keep pace with continued growth. Equally important is the environmental footprint of these materials, a concern that is especially pressing in regions with ambitious climate policies. In this article we will focus on the case of copper. We will discuss its availability on the market and have a look upstream in the supply chain of copper wire rod, used for manufacturing the Continuously Transposed Conductors (CTC) from which transformer windings are composed. We will shed a light on the various production routes, the options for recycling and their limitations, and the way the associated carbon emissions can be reduced.

KEYWORDS:

copper; CTC; copper supply chain; wire rod; copper cathodes; recycling; recycled content

Global copper reserves are estimated at 1,000 Mt — several decades' worth at current extraction rates (23 Mt in 2024) — with a further 470 Mt locked in products currently in use, the so-called urban mine

1. Copper demand and availability

Major global trends such as the energy transition and digitalisation, combined with the well-known dependence of electricity infrastructure on copper, may raise concerns about the impact of these developments on copper demand and availability. What is often overlooked, however, is that both electricity consumption and copper demand have grown strongly and consistently since the dawn of the electrical era, continuously driven by the emergence of new applications for electricity. The Critical Minerals Data Explorer of the International Energy Agency (IEA)[1] projects global copper demand across a broad range of scenarios and datasets. According to these projections, copper demand is expected to grow steadily at between 1.6% and 2.6% per year through to 2050 — figures that are entirely consistent with the historical average growth rate of approximately 3% per year recorded since 1900. While the drivers of growth have evolved over time, the underlying growth rate has remained remarkably stable.

There is sufficient copper in the ground to meet this growing demand. Global copper reserves are estimated at 1,000 Mt — several decades' worth at current extraction rates (23 Mt in 2024) — with a further 470 Mt locked in products currently in use, the so-called urban mine. Copper availability is therefore not the constraint, but meeting rising demand will require a scale-up of both primary mining and secondary recycling. Translating the resources into market-ready supply depends on a complex interplay of social, economic, legal, environmental, and infrastructure-related factors. In the near term, a healthy pipeline of new mining projects and mine extensions is already under development, pointing to an expected annual growth in mining capacity of 3.3% — comfortably ahead of projected demand. Over the medium and longer term, sustained commitment from all stakeholders will be essential to ensure that mining capacity keeps pace with demand growth. Governments can play a key role by streamlining permitting processes and avoiding unnecessary delays, while mining companies can continue to innovate and extract greater value from existing resources. Optimising copper recycling pathways, though not a silver bullet, can also make a meaningful contribution to closing any supply gap. A closer look

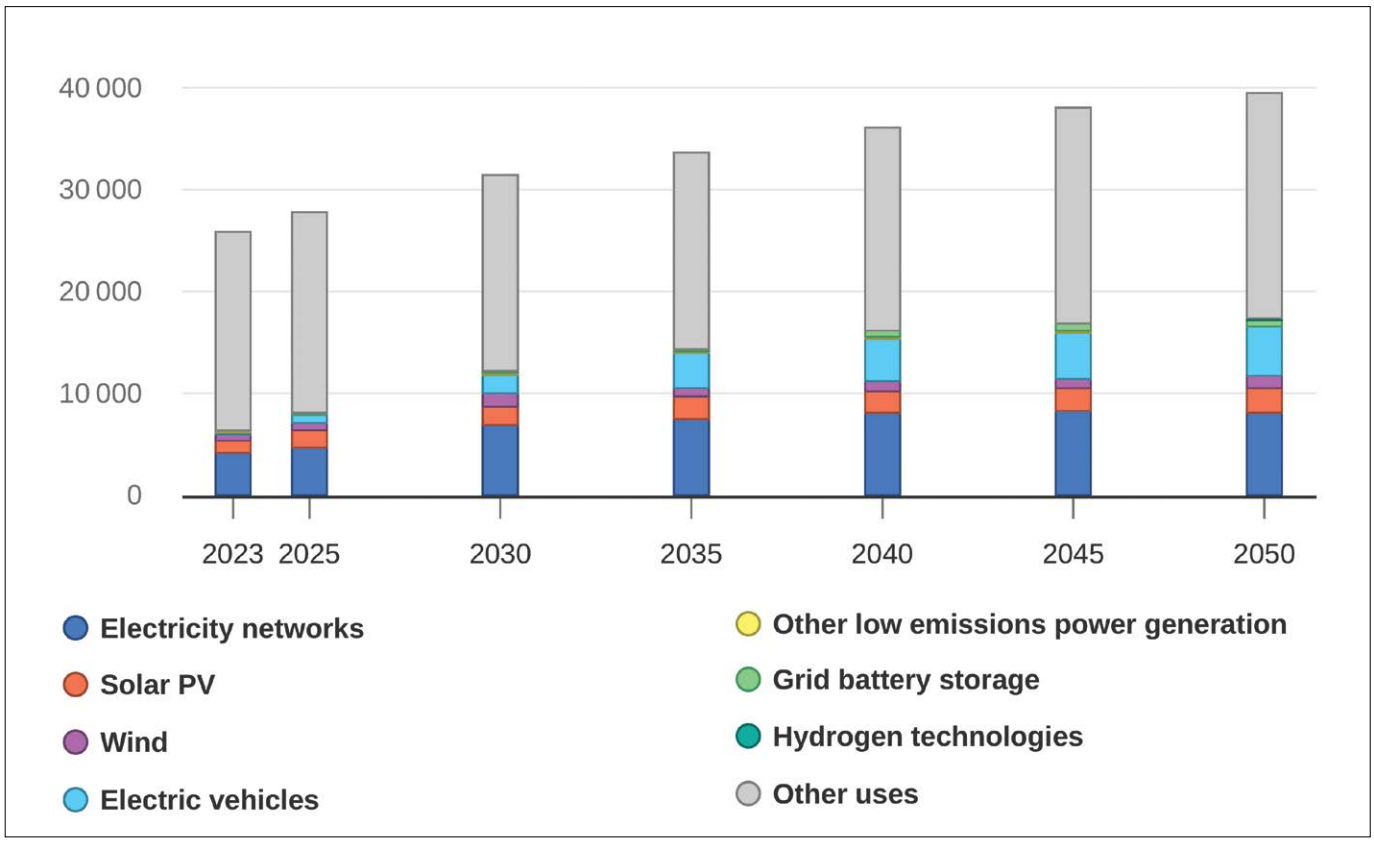

Figure 1. The projected global demand growth for copper, in ktpa, up to 2050, as predicted by the IEA in the Announced Pledges Scenario (assuming all announced ambitions and targets for will be realized)[1]

[1] https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer

at the copper value chain will help to illustrate how all of these elements fit together.

2. The various production routes of copper wire rod

The most established route for copper production — though certainly not the only one — is pyrometallurgical smelting and refining of primary material sourced from copper mines. This route (#2 on Figure 3) accounts for approximately 54% of global copper output.

The process begins with an initial purification stage, typically carried out at the mining site, involving crushing, grinding, and waste separation through flotation. The resulting copper concentrate is then transported to an industrial facility, where it undergoes smelting, converting, and fire-refining to achieve further purification, ultimately yielding a copper anode. A subsequent electrolysis process removes residual impurities, transforming the anode into a copper cathode with a purity of 99.99%, which can then be melted for wire rod production.

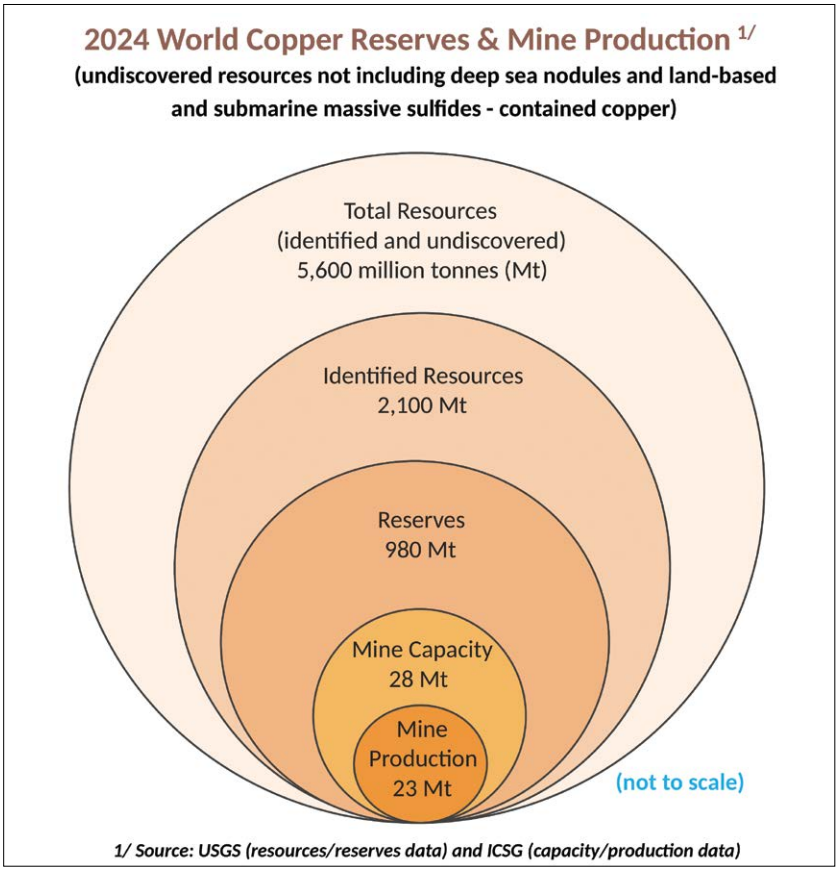

Figure 2. The availability of copper below and above ground (The World Copper Factbook, 2025)

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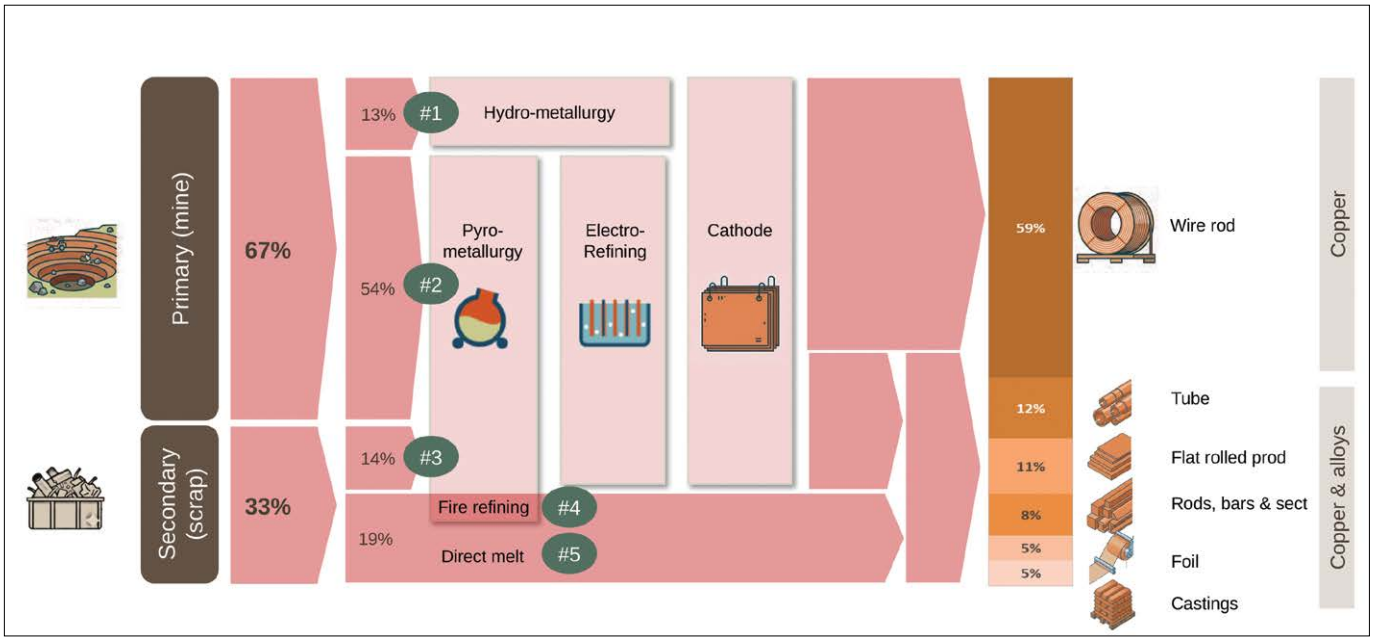

Figure 3. Overview of the different production routes of copper and copper alloys (Source: ICSG and IWCC statistics, 2024)

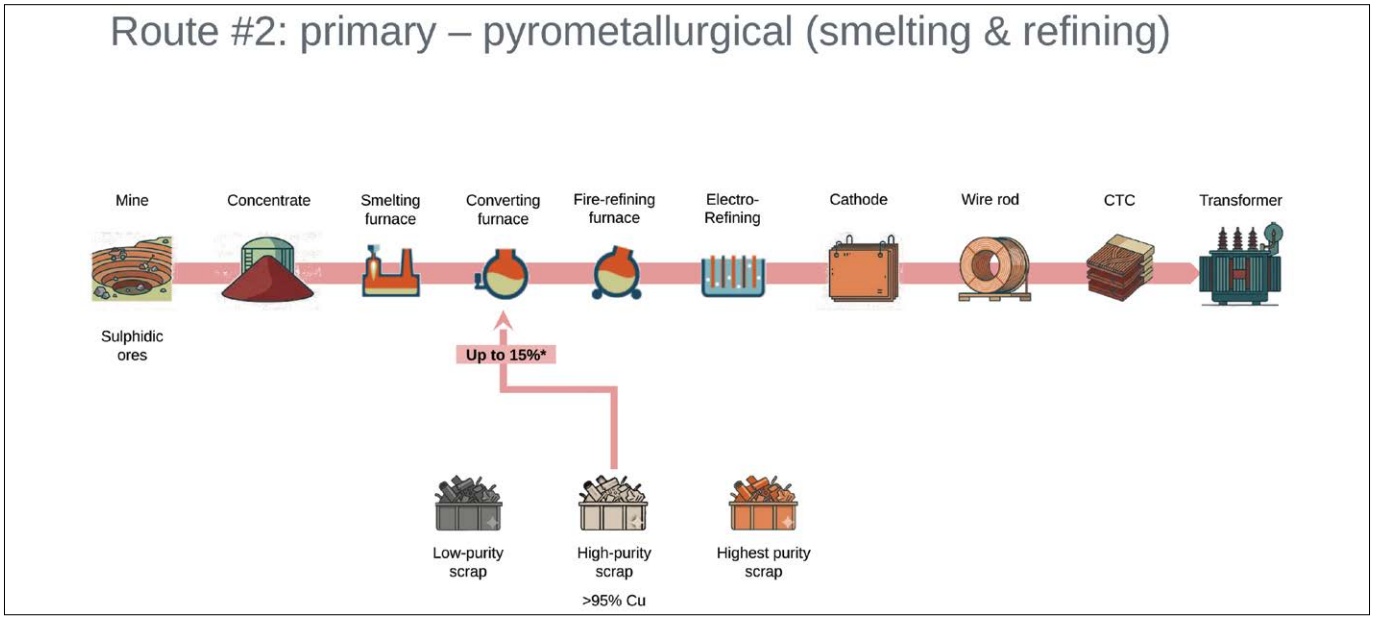

Figure 4. The most classical route for the production of copper for transformer windings, using mainly primary material that goes through pyrometallurgical refining methods

The hydrometallurgical route is unique in that it processes exclusively primary copper

Although this route primarily processes primary copper, up to 15% of high-purity scrap (> 95% Cu) is introduced for technical reasons. The scrap copper is added as a coolant to the converting furnace to control the temperature of the exothermic reactions. As a result of this practice, CTC manufacturers may have recycled material incorporated into their products without even knowing.

The hydrometallurgical route (#1 on Figure 3) is unique in that it processes exclusively primary copper. It employs solvent extraction to advance directly from copper ore to electro-refining in a single step. About 13% of all global copper production is produced with this technology.

When it comes to the processing of copper scrap, three more routes exist beyond the addition of scrap to primary copper smelters. The most common is the pyrometallurgical route using 100% secondary material (route #3 on Figure 3). This route can accommodate any type of scrap; however, the point of

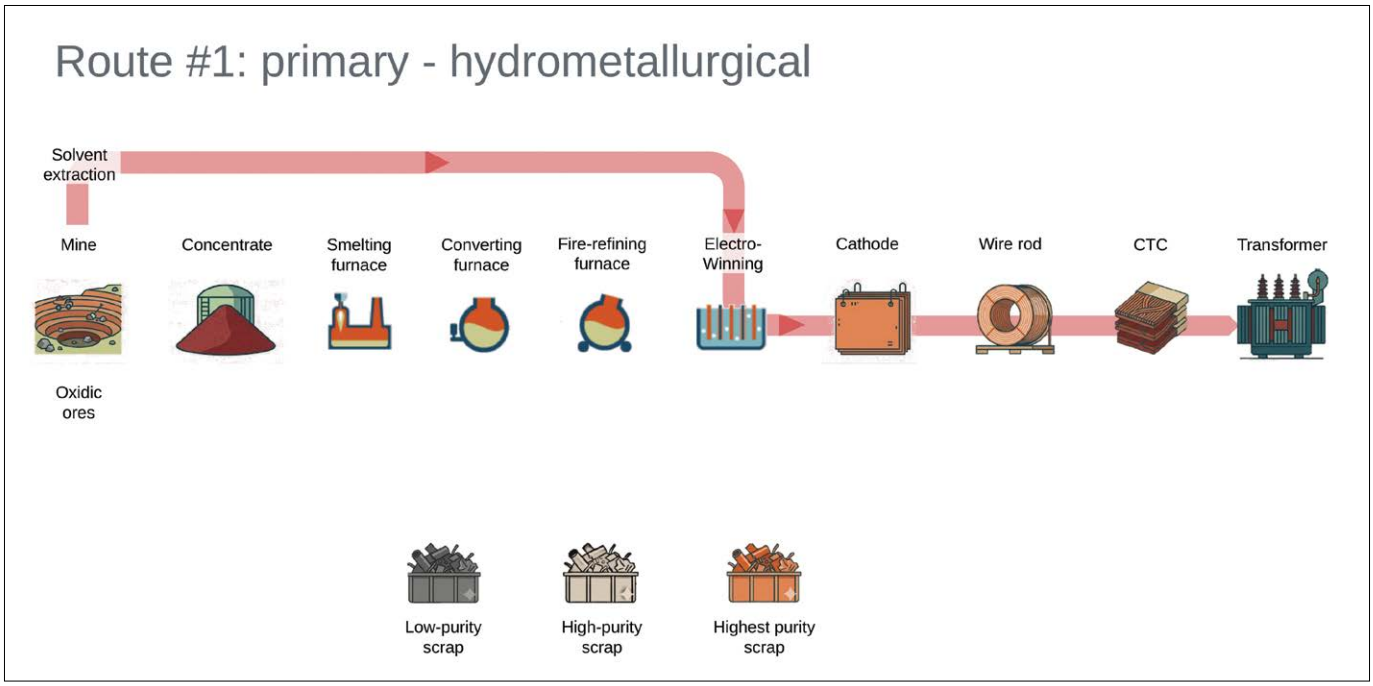

Figure 5. The hydrometallurgical route, processing exclusively primary copper

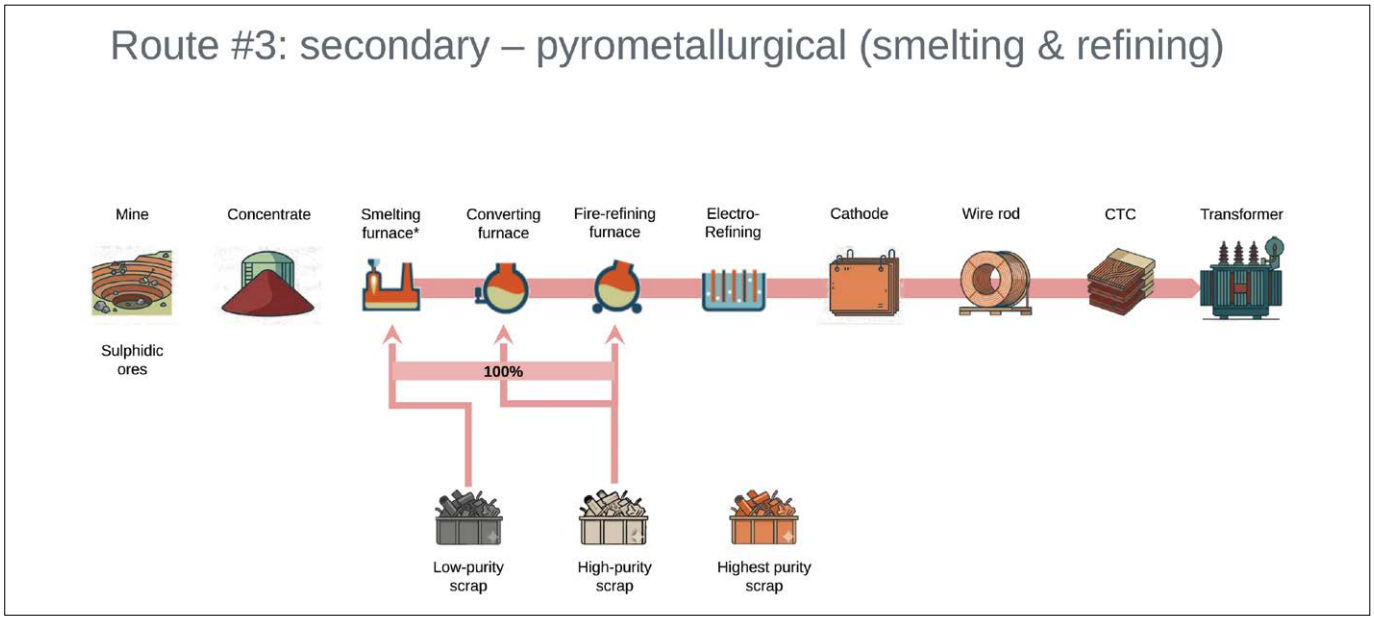

Figure 6. The pyrometallurgical production route with 100% secondary material – often called a "secondary smelter". Depending on its purity, scrap can be added at various stages

entry into the process depends on the scrap's purity level — lower-purity scrap is fed into the first step (the smelting furnace), medium-purity scrap into the second step (the converting furnace), and higher-purity scrap directly into the fire-refining process (see Figure 6). The higher the scrap purity, the fewer processing steps are required, and the lower the associated energy consumption and carbon emissions. This route concludes with electro-refining, producing cathodes of a purity level comparable to those described in route #2.

For scrap of sufficiently high purity (typically above 93%), a single fire-refining step may be sufficient for purification, bypassing electrorefining and any other intermediate processing (route #4 on Figure 3). This process is used to produce Fire Refined High Conductivity (FRHC) wire rod. Since electrorefining is omitted, certain elements cannot be fully removed (Ni, Sn, Ag, Au, Pb), which is why FRHC wire rod is generally intended for less demanding applications such as building wire, power cable, or conventional coil winding. However, strict control of the input material can

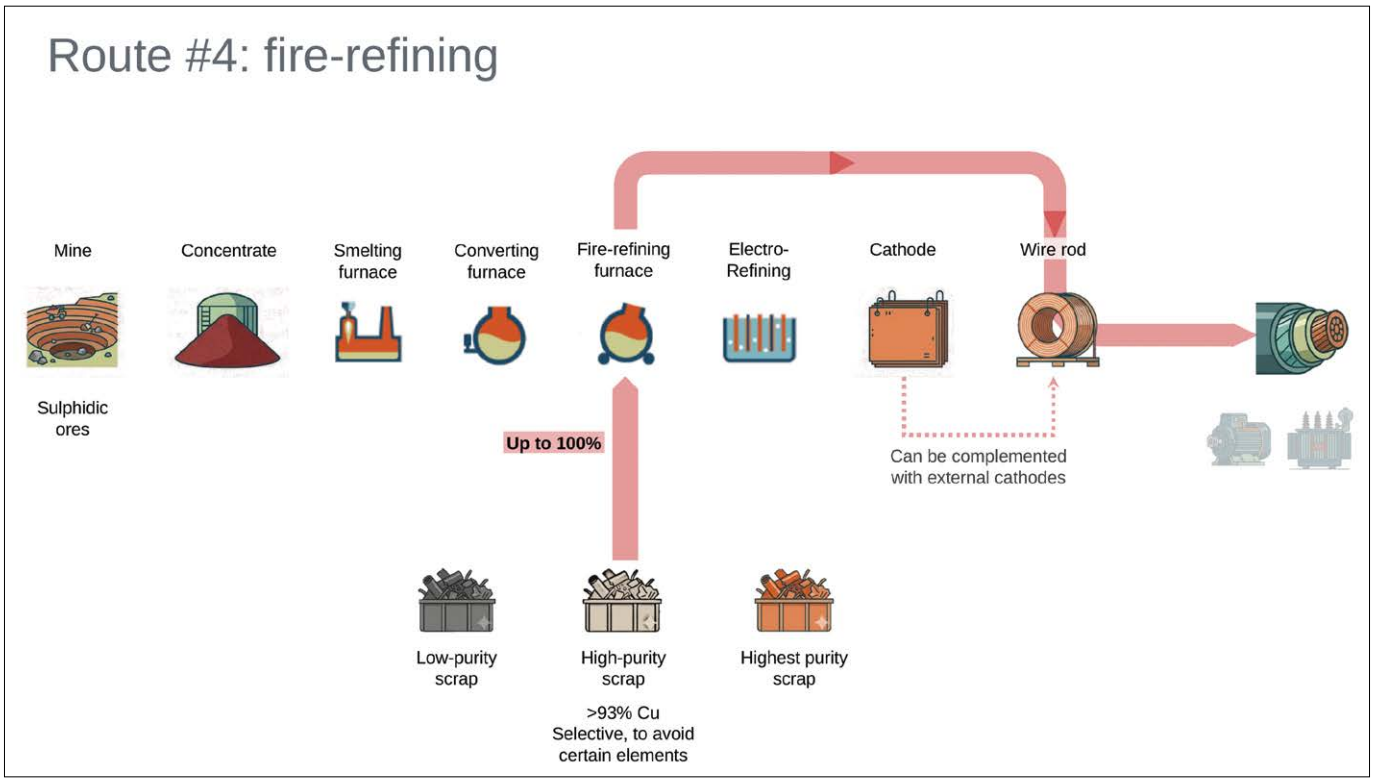

Figure 7. Fire Refined High Conductivity (FRHC) wire rod is produced from high-purity scrap through a single fire-refining step

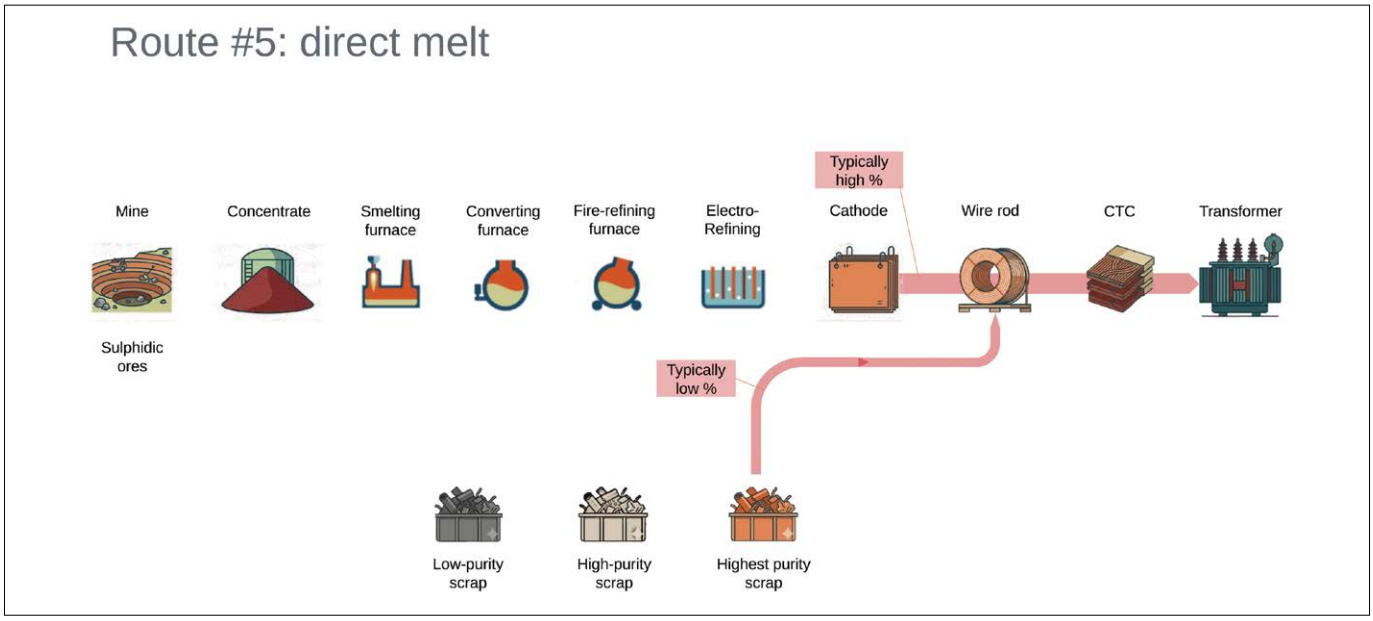

Figure 8. Scrap with a very high purity (> 99.995% Cu) can be melted directly for the production of semi-fabricated products, without any purification steps

When used for wire rod production, direct-melt copper is usually mixed with copper cathodes

prevent undesired alloying elements from appearing in the end product, making FRHC wire rod potentially suitable for high-conductivity copper and more demanding applications such as CTC.

For scrap of very high purity (> 99.995% Cu), combined with strict input control, semi-fabricated copper products can be produced through direct melting, without any purification steps (route #5 on Figure 3). When used for wire rod production, direct-melt copper is usually mixed with copper cathodes. It is, however, more commonly applied to semi-fabricated products with less demanding specifications.

Wire rod producers often blend material from different routes and sources, depending on market availability and the quality requirements of the end-use application. All wire rods must meet demanding specifications in terms of electrical conductivity, ductility, and

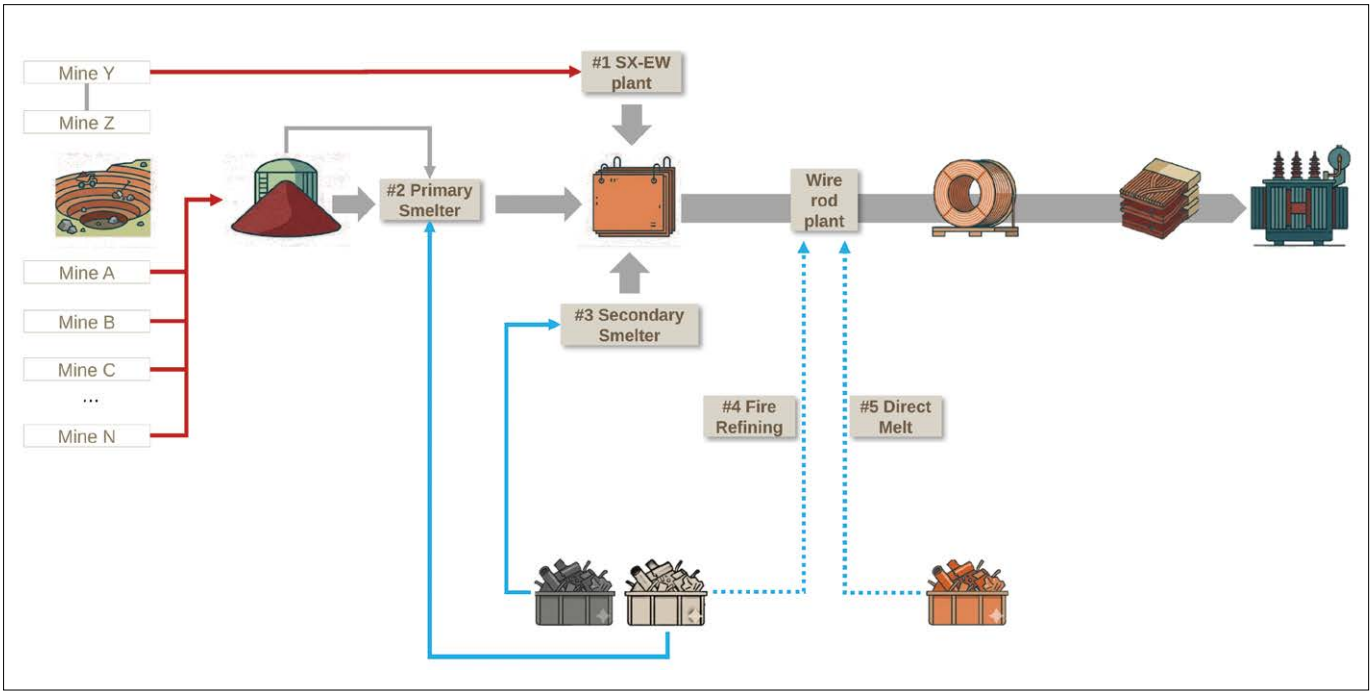

Figure 9. An overview of the five production routes from copper ore, or copper scrap, to wire rod and CTC

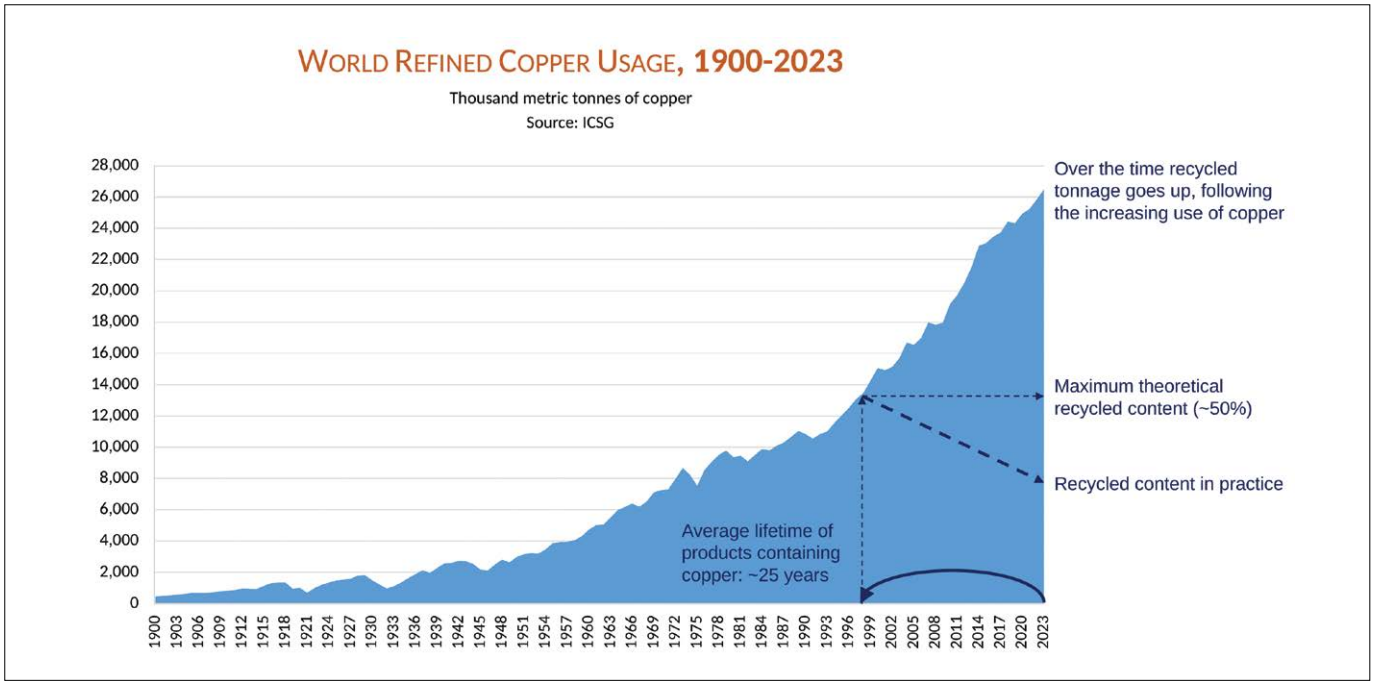

Figure 10. The amount of copper scrap that becomes available for recycling is equal to what was introduced into the market 25 years ago (the average lifetime of copper-containing products)

drawability, to which additional requirements may apply for applications such as CTC or very fine wiring. As a result, the majority of commercial wire rod is produced from Grade A cathodes, incorporating varying combinations of primary and secondary source material, while smaller quantities are produced via fire-refining or — where end-quality requirements are less stringent — direct melting.

Given the mixing of various material sources at different stages of the production process, assessing the embedded environmental impact of wire rod and CTC requires close collaboration and traceability across the entire value chain.

3. Recycling and primary copper decarbonisation

Given how well established copper recycling routes already are, it is tempting to view increased use of recycled material as a silver bullet — simultaneously improving the availability, circularity, and decarbonisation of copper. For an individual CTC manufacturer, boosting recycled content may indeed look like a straightforward strategy. However, because the copper recycling industry already absorbs essentially all available scrap, such a market-pull strategy for recycled content cannot produce any meaningful change at the broader level.

Given how well established copper recycling routes already are, it is tempting to view increased use of recycled material as a silver bullet

Market mechanisms currently direct copper scrap toward the path of least effort, which generally also means the lowest energy consumption and carbon emissions. Recycled-content requests from end-users or regulatory mandates therefore risk distorting these well-functioning recycling streams, potentially leading to a net increase in the energy consumption of aggregated copper production.

It is also worth remembering that one can only recycle what has already been used: since most copper applications have a long service life — typically 25 years — and copper demand was roughly half of today's levels 25 years ago, the theoretical maximum share of recycled material is around 50% of current demand, a figure reduced further in practice by inevitable losses during end-of-life collection and separation. The conclusion, then, is that individual end-users or market regulators demanding higher recycled content would simply divert recycled copper away from others, with no net benefit at the global level.

Consequently, both primary and secondary copper are necessary to meet increasing demand, and any strategy for decarbonising copper CTC must include the decarbonisation of primary copper. Mining and concentration account for approximately 70% of the carbon footprint of primary copper production, with a further 23% attributable to smelting and refining. The global average carbon intensity of primary copper has been declining steadily from 5.4 t CO_2e/t Cu in 1990 to 4.6 t CO_2e/t Cu in 2018, driven primarily by the decarbonisation of electricity, and is projected to decrease further in the near future. Key levers include the further decarbonisation of grid electricity, the electrification of mining equipment, alternative fuels such as hydrogen and e-fuels, and energy efficiency improvements. Within this context, each copper producer will follow its own trajectory, depending on the availability of these decarbonisation levers at competitive cost. Downstream stakeholders can play a meaningful role in facilitating this transition through

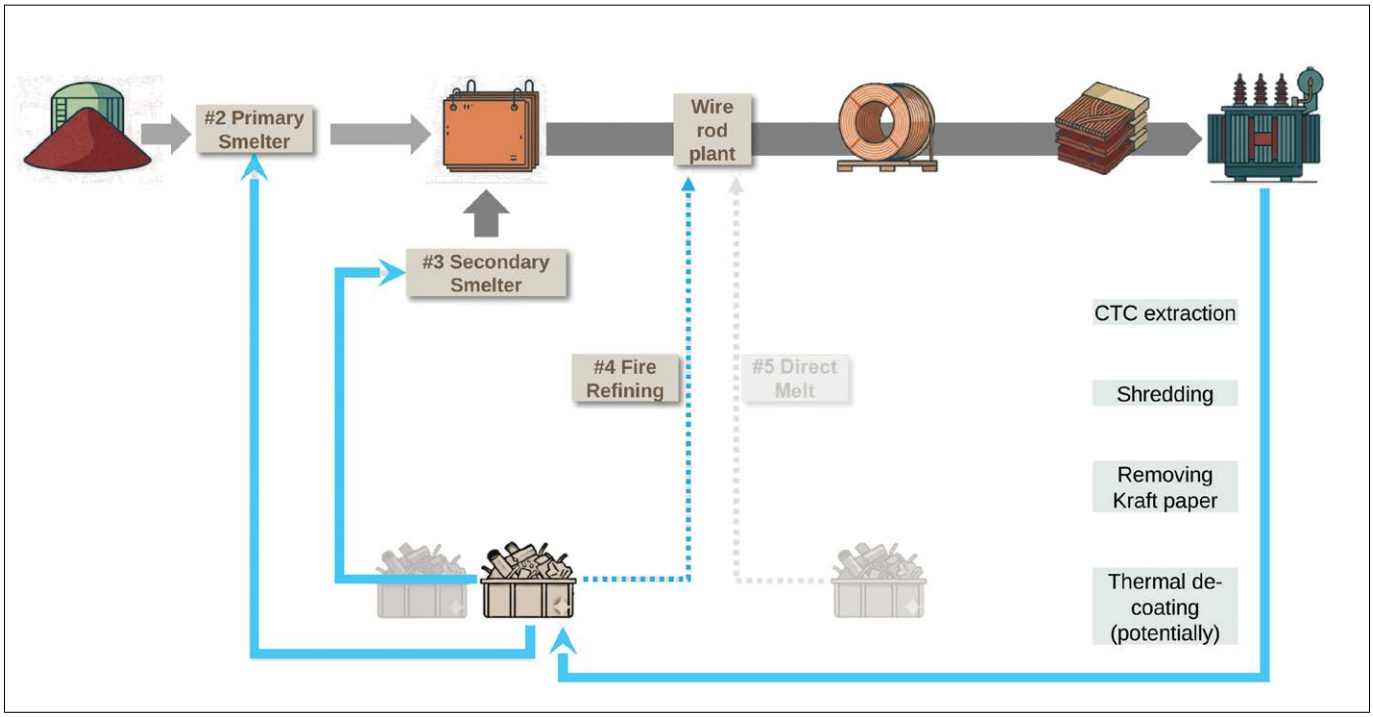

Figure 11. The potential recycling routes for copper scrap from transformer windings

positive engagement and demand-side signals.

Improvements to the recycling process can also contribute meaningfully to decarbonisation. Through effective separation and sorting at the end of a transformer's service life, copper can be recovered at the highest possible purity, preventing high-purity scrap from being downgraded.

4. Conclusions

The copper supply chain serving transformer windings is more complex than it might appear. Multiple production routes coexist, each with different implications for recycled content, energy use, and carbon emissions. Understanding this complexity is a prerequisite for developing sustainability strategies that are genuinely effective rather than merely well-intentioned.

Two conclusions stand out. First, there is no reason to fear a shortage of copper in the short and medium term, provided that the necessary investment in mining capacity, permitting, and innovation is sustained. Second, recycled content alone is not a credible decarbonisation strategy. As the scrap availability is structurally limited by the long service life of copper products, demanding higher recycled content does not reduce the total environmental burden — it merely redistributes it.

When it comes to the embedded carbon emissions, the currently available levers that can make a substantial difference are an accelerated decarbonisation of grid electricity, electrification of mining operations, and the development of recycling routes that preserve scrap purity. For transformer manufacturers and CTC producers, this points to a clear role — not only in optimising their own processes, but in sending credible demand-side signals to upstream suppliers that reward lower-carbon production.

Authors



Bruno De Wachter has 25 years' experience as a freelance engineer-copywriter in B2B and EU advocacy communication. He combines his technical background with a passion for employing precise forms of expression and a wide-ranging knowledge of the energy transition and policy-making. Since 2011 he has been an in-house consultant and copywriter for the International Copper Association on topics related to renewable energy systems, transformers, motors and electrical safety.



Fernando Nuño graduated as an energy engineer in Bilbao (Spain) and IFP School (France) in 1998. He worked in the development of combined heat and power plants at Air Liquide company, then he joined the French Energy Regulatory Commission, where he was in charge of electricity markets regulation. Later on, he worked in the automotive sector at Renault powertrain division, before joining the International Copper Association in 2007, where he has been in charge of regulatory and technology aspects of copper-based technologies, notably transformers, cables and motors. He also manages marketing campaigns and leads multiple publicly funded EU Horizon projects.